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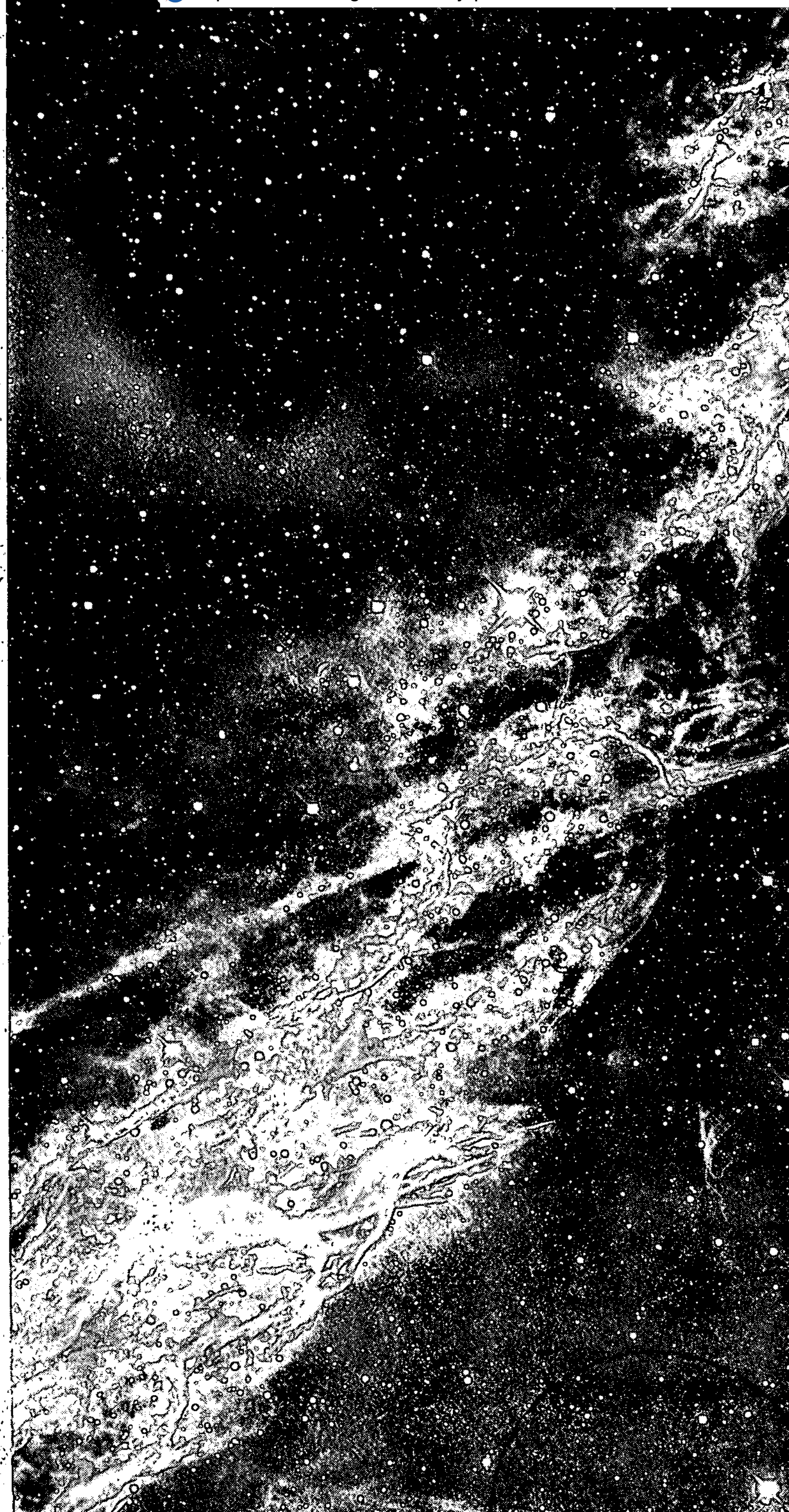

Report No. M-28

COMET RENDEZVOUS MISSION STUDY

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COMET RENDEZVOUS MISSION STUDY

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for

Planetary Programs
Office of Space Science and Applications
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Approved by:

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FOREWORD

This report is the final documentation on all data and information required by the task - Comet Rendezvous Mission Study. The study was conducted by IIT Research Institute for NASA Headquarters, Planetary Programs, Office of Space Science and Applications under Contract No. NASW-2144. The work reported herein represents the first comet rendezvous mission study sponsored by NASA and was performed during the time period May 1970 to June 1971. The major results were presented in an oral briefing to NASA Headquarters in June 1971 and were also communicated to the Cometary Science Working Group (O'Dell and Roberts, 1971) and to the contractor performing a follow-on study for JPL (TRW, 1972).

The writing style of this report is somewhat unusual in that the typical "free-flowing" text is not followed. Rather, the major information content of the study results is contained in the illustrations (Tables and Figures). This is supplemented by a concise description and explanation provided on the facing page to each illustration. To further aid the reader, each section of the report includes a list of illustration titles and a written summary of the material at the beginning of each section. It is hoped that the reader will find this report style an efficient vehicle for obtaining the information he desires.

SUMMARY

The primary objective of this report is to establish the value and characteristics of comet rendezvous missions. Four periodic comets with perihelia between 1980 and 1986, Encke, d'Arrest, Kopff and Halley, were recommended in a previous study as good candidate missions (Friedlander, et. al., 1970). Comet P/Halley is well known because it is easily seen once each 76 years with the unaided eye. Since P/Encke has the shortest period and smallest perihelion distance, astronomers have studied it more extensively than the other periodic comets. The other two are typical short-period comets. All these comet apparitions are especially favorable for rendezvous missions because of early Earth-based comet recovery, good opportunities to view their activity from Earth and reasonable launch vehicle and trajectory requirements for nominal payloads.

Answers to the questions listed in the left-hand column of Figure S-1 are required to understand the origin of comets and the dynamics of cometary phenomena. The first six questions are about the nucleus and the composition of cometary material and are indirectly related to the problem of comet origin. The remaining ones are concerned with the activity observed near perihelion. A comet flythrough mission would achieve some of these scientific objectives. However, during a rendezvous mission data can be obtained which is pertinent to all of these questions since the observation time is much longer and the opportunities for spatial investigation are varied. For each question the useful science instruments are indicated with an "X". Simultaneous observations of the comet from the spacecraft and the Earth will be complimentary, but more importantly this will improve the interpretations of spatial, spectral and temporal observations of other comets, both in the past and in the future. Equally important is the coordination of in-situ and remote sensing measurements which will allow

FIGURE S-1 INSTRUMENT USE FOR COMET RENDEZVOUS MISSIONS

QUESTIONS \ INSTRUMENTS	SCIENCE TV	UV, V SPECTROMETER	PHOTOMETER/RADIOMETER	MASS SPECTROMETER	SOLID PARTICLE DETECTOR	PLASMA ANALYZER	MAGNETOMETER	PLASMA WAVE DETECTOR	RADIO TRACKING
WHAT IS THE COMET NUCLEUS LIKE?	X		X						
WHAT HAPPENS TO THE NUCLEUS AT PERIHELION?	X		X	X	X				
WHAT HAPPENS TO THE NUCLEUS AT APHELION?	X		X						
WHAT IS THE COMPOSITION OF THE PARENT MOLECULES?				X					
WHAT IS THE COMPOSITION OF THE DUST PARTICLES?					X				
WHAT NON-GRAVITATIONAL FORCES ACT ON THE NUCLEUS?									X
HOW ARE MOLECULES AND IONS FORMED?		X		X		X			
HOW ARE MOLECULES AND IONS DISTRIBUTED IN SPACE?		X		X		X			
HOW DOES THE COMET INTERACT WITH THE SOLAR WIND?						X	X	X	
HOW LARGE ARE THE SOLID PARTICLES?			X		X				
WHAT CAUSES SUDDEN CHANGES IN COMET ACTIVITY?		X		X		X	X	X	

the conditions near the spacecraft to be related to those farther away.

A nominal science instrument package is assembled using currently available or proposed devices. In addition to those listed across the top of Figure S-1, the package includes an approach acquisition TV. The science TV obtains images of the nucleus during the circumnavigations. The mass spectrometer and a UV, V spectrometer both measure molecular and ion abundances. The photometer/radiometer and the solid particle detector both measure the dust in the coma. New instrument developments are needed to determine the composition of more energetic ions and of solid particles. The magnetometer, plasma analyzer and plasma wave detector are included to observe the interaction between the comet and the solar wind and magnetic field. Allowing 10% for the desired improvements, the total weight, power consumption and data rate for the nominal science instruments are 70 kg, 90 w and 2.6 x 10^8 per day respectively.

To take full advantage of rendezvous to study comet activity, an arrival date of 50 days before perihelion and a mission duration of about 100 days are required. A station-keeping program is needed to investigate the spatial structure of the comet. Circumnavigations of the nucleus at a distance of about 100 km will allow closeup examination of the center of activity and source of material. Radial traverses to about 20,000 km will study changes in composition, the effects of the solar wind interaction and the sources of both the plasma and dust tails. A deployed probe is suggested for in-situ exploration of the nucleus. Since there is little interference with the program to explore the coma and no additional hazard to the spacecraft, this concept provides high quality scientific data for a modest increase in spacecraft complexity. The weight of the probe is taken as 60 kg.

The weights of spacecraft subsystems given in Table S-1 are estimated using scaling laws. Briefly the requirements are 70 kg of science instruments, a 4 kbps data rate capability at 2.0 AU, storage of one day's data, a total power of 250 w at 2.0 AU and 200 m/sec for midcourse and stationkeeping maneuvers. The subsystem differences are small between a ballistic spacecraft and an integrated SEP design. The latter obtains power and maneuvering capability from the SEP systems. However, increases were made in the computer/sequencer and attitude control subsystems to account for the additional complexity and larger moment of inertia of an SEP design. The comet environment requires the addition of meteroid protection, however, the amount needed is uncertain. In addition the current large field-of-view cannot be used for attitude reference when the spacecraft is near the comet nucleus. Jettison of the SEP system at rendezvous offers no advantages over the integrated design, and would, in fact, require a larger net payload.

Rendezvous missions to the short-period comets Encke, d'Arrest and Kopff can be accomplished with solar electric propulsion or ballistic (chemical propulsion) systems launched by Titan/Centaur vehicles. The baseline mission selections are given in Table S-2. The ballistic flight mode requires a high-energy retro stage ($I_{sp} \approx 400$ sec) and has a marginal payload capability even with the 7-segment Titan needed for the Encke and d'Arrest missions. In comparison, solar electric propulsion has far greater performance potential in terms of significantly shorter flight times and greater payload margins. Using the programmed Titan 3D/Centaur and a 15 kw SEP powerplant, the flight time to d'Arrest and Kopff is only 2 years. Flight time to Encke is 2.6 years (1980 apparition), but can be reduced to 2 years if the mission is delayed to the 1984 apparition.

There are important tradeoffs in the selection of a baseline SEP mission. Parameters of interest are arrival time

TABLE S-I

COMET RENDEZVOUS SPACECRAFT MODELS

SPACECRAFT SUBSYSTEM	BALLISTIC SPACECRAFT	SOLAR ELECTRIC SPACECRAFT
SCIENCE INSTRUMENTS	70 kg	70 kg
SCAN PLATFORM	15	15
COMMUNICATIONS	28	28
ANTENNA	12	12
DATA STORAGE	14	14
COMPUTER/SEQUENCER	15	20
ATTITUDE CONTROL	45	55
POWER SUPPLY	15	-
BATTERY	10	10
POWER CONDITIONING	11	11
CABLING	20	20
THERMAL CONTROL	12	12
METEOROID PROTECTION	10	10
STRUCTURE	88	88
SUBTOTAL	365 kg	365 kg
10% CONTINGENCY	40	40
PROPULSION	35	5
PROBE	60	60
TOTAL	500 kg	470 kg

TABLE S-2

BASELINE MISSION SELECTIONS

COMET/YEAR	MISSION MODE	LAUNCH DATE	FLIGHT TIME (YRS)	ARRIVAL DAYS BEFORE T_P	THRUST TIME (HRS)	LAUNCH VEHICLE	RENDEZVOUS PAYLOAD (KG)	
							NOMINAL	MAXIMUM
ENCKE/80	SEP	3/ 2/78	2.63	50	13,500	T3D/CENT	500	1100
	BALLISTIC	2/23/77	3.51	100	-	T3D(7)/CENT	500	500
d'ARREST/82	SEP	8/13/80	2.03	25	13,700	T3D/CENT	500	690
	BALLISTIC	8/14/77	4.96	50	-	T3D(7)/CENT	500	520
KOPFF/83	SEP	7/14/81	2.03	25	11,600	T3D/CENT	500	630
	BALLISTIC	7/17/79	3.95	50	-	T3D/CENT	500	500
ENCKE/84	SEP	2/26/82	1.97	40	15,000	T3D/CENT	500	560
	BALLISTIC	3/ 4/80	3.93	50	-	T3D(7)/CENT	500	500
HALLEY/86	NEP	5/16/83	2.60	50	14,800	T3D(7)/CENT	500	930
	SEP/GA	8/25/77	8.32	50	27,000	T3D(7)/CENT	500	500

SEP P_0 = 15 KW, I_{SP} = 3000 SEC

NEP P_E = 100 KW, I_{SP} = 6000 SEC

BALLISTIC SPACE-STORABLE RETRO I_{SP} = 400 SEC

GA JUPITER GRAVITY-ASSIST

relative to perihelion, flight time, powerplant size, and propulsion on-time. In general, payload gains are affected by optimizing any of these parameters. Alternatively, when more than adequate payload is available, certain parameters may be selected "suboptimally" in order to enhance engineering design goals and mission reliability. A SEP power level of 15 kw and a maximum of 15,000 hours of thrust time are such choices. This is thought to be the proper design procedure, even in preliminary mission analyses.

Practical accomplishment of the very difficult Halley rendezvous depends upon the development and availability of nuclear-electric propulsion by 1983. A 100 kw NEP system launched by the Titan 3D(7)/Centaur can deliver more than adequate payload in a flight time of only 2.6 years. Propulsion time is held to 15,000 hours for the nominal 500 kg payload. Use of the proposed Shuttle/Centaur/NEP would allow even further reduction in propulsion time.

Velocity errors at Earth departure and thrust execution errors enroute will cause very large ($1-2 \times 10^6$ km) terminal deviations if left uncorrected. However, the effect of these errors can be measured by the DSN, and trajectory corrections can be made at moderate propellant cost - even in the case of ballistic flights. The ballistic mission to P/Encke requires a total guidance ΔV of about 100 m/sec using 3-4 impulsive maneuvers. In the case of the SEP mission, it was shown that coast periods during the heliocentric transfer are important in that they allow the DSN to recover high accuracy tracking of spacecraft position and velocity. The propellant chargeable to all SEP guidance maneuvers is less than 10 kg.

The major error source at rendezvous is the comet's ephemeris uncertainty. Even after comet recovery by Earth-based telescopes the comet's position may be uncertain by many thousands of kilometers. Reduction of this error to the order of 10-100 km can be accomplished only by on-board tracking and trajectory corrections during the approach phase (about 50 days before rendezvous). A non-zero value for the miss distance (about 1000 km is adequate) is required to reduce the range uncertainty. The necessary information can be obtained by a vidicon system which transmits pictures of the comet against a stellar background. However, a study should be made of other systems (e.g., a scanning photometer) which are less complex and less expensive.

To accomplish the recommended stationkeeping program requires an impulsive ΔV of between 69 m/sec (P/Halley) and 167 m/sec (P/Encke). These maneuvers can be performed with the SEP system using less than 6 kg of propellant and less than a 4% duty cycle (2.4 days of thrust over a 60 day period).

Many of the details of SEP comet rendezvous missions are illustrated in the study for the 1980 apparition of P/Encke. This mission was selected because P/Encke is scientifically more interesting than the other short-period comets and because two apparitions are available (1980 and 1984). An Encke mission is somewhat more demanding so that not all conclusions about it apply to the P/d'Arrest and P/Kopff missions. The 1980 mission is launched in March 1978, although a 60-day launch window is available at a cost of 15 kg of propellant. Six ion thrusters, each having a 2:1 throttling capability and rated at about 2.8 kw, are used to match the required power profile. Maximum operating time of any single thruster is less than 6000 hours and between one and five thrusters are in a standby mode during the propulsion phase. There is a wide variation of optimum thrust direction relative to the sunline which may be accommodated using rotatable solar arrays. Near the perihelion at 0.34 AU it will be necessary to rotate the arrays to keep their temperature at acceptable levels.

Because the comet is approached along the sunline the illumination of the nucleus is good and on-board recovery occurs 60 days before rendezvous at a range of 4×10^6 km. Rendezvous occurs on 17 October 1980 (50 days before perihelion) when P/Encke is 0.26 AU from the Earth. During the next ten days when the nucleus is investigated and the probe deployed the data rate is about 2.6×10^8 bits per day. There are large variations in the clock and cone angles of the Earth so the spacecraft should be equipped with a high gain antenna with two degrees of freedom. Data and commands can be exchanged between the spacecraft and the DSN network for at least 20 hours per day during all mission phases.

Further study of rendezvous missions to the periodic comets at the Phase A level, with emphasis on a solar electric mission to P/Encke at either the 1980 or 1984 apparition, is warranted.* Areas requiring more detailed analysis include: 1) a model for the comet environment, 2) a design for a nucleus probe, 3) the performance penalty for constrained (non-optimum) thrust vector steering and 4) an engineering design for the spacecraft which considers thermal control and the pointing requirements for the science instruments, the antenna and the thrust vector. A flythrough mission would simplify the solution of some of these engineering problems. Technology advances are needed to develop the remote control techniques and/or on-board decision making system to be used during the stationkeeping program, the approach guidance TV (or alternate system) and new science instruments for composition determinations of solid particles and energetic ions.

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* For budgetary reasons, NASA has decided that the subsequent comet rendezvous study (TRW, 1972) will concentrate on 1981 and 1982 launches to P/Encke.

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COMET RENDEZVOUS MISSION STUDY

1. INTRODUCTION

The renewed interest in comet exploration among NASA mission planners and the scientific community is due in part to current investigations of the rendezvous mission mode. Rendezvous operations allow the spacecraft to match orbits with the comet and thus have several months to monitor the variations in physical activity as the comet approaches and passes through perihelion. The science measurement profile and return of temporal data are greatly enhanced by this mission mode.

A recent study by Astro Sciences/IITRI provided a comprehensive survey and compendium of data on periodic comet rendezvous opportunities (Friedlander, Niehoff and Waters, 1970). A number of promising mission opportunities were identified from the standpoint of trajectory requirements, launch vehicle/payload capabilities, and Earth-based sighting conditions. Four comet apparitions were recommended for a follow-on mission study which is the subject of this report. These comets and their associated years of perihelion passage are:

1. Encke (1980, 1984)
2. d'Arrest (1982)
3. Kopff (1983)
4. Halley (1986).

Of all the short-period comets, P/Encke has the shortest period of 3.3 years and has received the most attention in terms of its prior observation and orbit analysis. It is still a fairly active body and is probably the most scientifically interesting comet of the short-period group. Comets P/d'Arrest and P/Kopff are similar in characteristics both as comets and as mission opportunities. Their orbital periods are about 6.5 years and they have been observed much less frequently and are less active than P/Encke. Halley's Comet is undeniably a unique and interesting periodic comet. It is well known to both the public and scientific communities because of its naked-eye brightness and high activity. Halley's orbit is retrograde with a period of 76 years; the retrograde feature makes it a very difficult target for rendezvous.

The purpose of this study is to establish the characteristics and requirements of rendezvous missions to each of the above-mentioned comets. Specific study objectives are listed below:

1. Review theories and existing knowledge of comets.
2. Determine science objectives, measurements and instrumentation appropriate to the rendezvous mission mode.
3. Determine trajectory requirements and net spacecraft mass capability. Compare solar electric propulsion and ballistic delivery modes for missions to P/Encke, P/d'Arrest and P/Kopff; for missions to P/Halley, compare solar and nuclear electric propulsion modes.
4. Determine midcourse and approach guidance requirements.
5. Specify typical stationkeeping maneuvers and determine the ΔV requirements.
6. Estimate spacecraft subsystem requirements such as mass, power and data rate.
7. Recommend a preferred first-generation mission target and delivery mode, and identify problem areas requiring further study.

The analysis in this study is consistent with a pre-phase A level of effort. It is the first comet rendezvous mission study to be conducted for NASA and hopefully it will be useful to those engaged in the planning and design of future comet rendezvous missions. The results of this study were made available to the Cometary Science Working Group which met at Yerkes Observatory in June 1971 (O'Dell and Roberts). Some recommendations of that conference on science instruments were then incorporated into this rendezvous mission study. The results were also communicated to the contractor performing a follow-on study for JPL (TRW, 1972).

Organization of this report is as follows: Section 2 discusses the existing body of knowledge concerning theories of comet origin and activity, measured spectra, brightness and orbital characteristics, and pertinent science questions together with appropriate spacecraft measurements. The experiment definition, candidate science payloads, and instrument capabilities are presented in Section 3. In Section 4 the comet environment implications on spacecraft design are addressed, and the spacecraft subsystem models (weight, power, data rate) are developed. Section 5 presents the trajectory/payload characteristics, examines the trade-off considerations, and describes the baseline mission selections for each of the target comets and propulsion modes. Mission operations including midcourse and approach orbit determination and guidance, and comet stationkeeping maneuvers are treated in Section 6. Profile data for a solar electric mission to P/Encke are presented in Section 7.

2. SCIENTIFIC KNOWLEDGE AND OBJECTIVES

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SECTION 2 SUMMARY

Comets are small solar system bodies which become very active at their perihelia when gases are released from an icy nucleus by solar heating. The gases expand to form the comet coma. Solar energy also excites the molecules which then emit the familiar resonance fluorescence lines. Ions are also formed which are subsequently incorporated into the Type I comet tail. The coma and the Type II tail contain dust grains.

The primary goal of comet missions is to determine the origin and evolution of comets. Study of the nucleus and the composition of cometary material is, therefore important. A secondary objective is to understand the perihelion activity of comets, including the interaction with the solar wind and the formation of the observed molecules and ions.

This study considers rendezvous missions to the periodic comets, P/Encke, P/d'Arrest, P/Kopff and P/Halley. Comet P/Halley is the most brilliant of the four and is usually seen for several months with the unaided eye each 76 years. It has a retrograde orbit, both types of tails and is in many respects very similar to the spectacular new or parabolic comets. Since they are periodic comets a mission can be planned during their predictable returns to perihelion. Each can be recovered by an Earth-based telescope at least 150 days before perihelion to improve our knowledge of its orbit. During the period of greatest activity around perihelion all four comets are brighter than 12th magnitude and in a dark sky for at least one month. This will permit valuable simultaneous observation of the comet by the spacecraft and by Earth-based equipment. To properly carry out these investigations rendezvous with P/Halley and P/Encke must occur at least 50 days before perihelion while 25 days is adequate for the other two. A minimum of 100 days are required to study comet activity and extension of the mission for one year is desired to observe the nucleus in its quiescent state.

Considering the spatial extent of coma structure, a rendezvous exploration program is proposed that begins and ends with a circumnavigation of the nucleus. In addition to photography of the nucleus, this activity is valuable for determining the composition of parent molecules and for investigating processes in the inner coma. Included in the station-keeping program are excursions up to 20,000 km from the nucleus. At these distances the important phenomena to be observed are the contact discontinuity which separates the comet plasma from a turbulent mixture of comet and solar plasma and the origins of the ion and dust (Type I and Type II) tails.

COMET ORIGINS AND ORBITAL ELEMENTS

Comets are an interesting feature of our solar system. They display great activity only when near the sun. One group, the periodic comets, are confined to the same regions as the planets, while the other, larger group of new or parabolic comets spend almost all their time beyond 30,000 AU (Oort, 1950 and 1963). While those in the latter group are far more spectacular and scientifically more interesting, a periodic comet is an appropriate mission target because its orbit is known.

The periodic comets are presumed to be captured from the parabolic group by the action of successive perturbations, mainly by Jupiter. Quite possibly they are altered during the 10^3 to 10^6 years they are in short period orbits. The parabolic comets could be a well preserved remnant of the original planetary formulation process or a sample of interstellar material. In either case the composition is important and can be obtained by in-situ measurements of the comet. In addition an understanding of comet activity would contribute to our knowledge of interplanetary debris and the use of comets as probes of the interplanetary medium at high solar latitudes.

The orbital elements of the four target comets in this study are given here. P/Encke has the smallest period and perihelion distance of any periodic comet. P/d'Arrest and P/Kopff are typical periodic comets with about six year periods. P/Halley is noted for its 76 year period and retrograde orbit. In all cases the orbit includes the effects of planetary perturbations. These are significant for d'Arrest which has a close encounter (0.30 AU) with Jupiter in 1979.

Except for a four day delay in the perihelion date of Halley, non-gravitational effects are expected to be small (Marsden, 1970). An orbit which includes non-gravitational effects should be used in the final plans for a comet mission. For P/d'Arrest the planetary perturbations make it difficult to predict the non-gravitational accelerations.

TABLE 2-1

COMET ORIGINS AND ORBITAL ELEMENTS

		ENCKE	d'ARREST	KOPFF	HALLEY
PERIHELION DATE	T	12/6/80	9/18/82	8/18/83	2/9/86
PERIOD, YEARS	P	3.303	6.394	6.444	76.008
PERIHELION DISTANCE,AU	q	0.339	1.300	1.576	0.587
ECCENTRICITY	e	0.847	0.622	0.545	0.967
INCLINATION	i	11.95	19.59	4.73	162.24
LONGITUDE OF NODE	Ω	334.19	138.89	120.37	58.15
ARGUMENT OF PERIHELION	ω	185.98	176.93	162.78	111.86
OSCULTATION DATE		11/6/80	9/8/82	6/14/83	2/9/86
REFERENCE		1	2	1	3

1. Narin and Pierce, 1964
2. Narin and Rejzer, 1965
3. Brady and Carpenter, 1971

COMET MORPHOLOGY

The morphology of comets is illustrated by this photograph of P/Halley taken from Rahe, et. al. (1969). The radius of the coma (or head) is about 10^5 km. Clearly visible are the streamers in the type I or ion tail which was about 10^8 km long. A type II or dust tail was also observed but does not appear in this photograph. P/Halley is a very active comet and is easily observed near perihelion with the unaided eye. The three candidate short period comets, Encke, d'Arrest and Kopff are less bright (see Table 2-3) and only Encke has an ion tail; none of the three have dust tails.*

A nucleus is assumed to be the source of the comet's activity but it is too small (up to 20 km in radius) to be resolved. During perihelion passage the rate at which molecules are released from the nucleus is typically 10^{30} per second. Within one thousand kilometers of the nucleus collisions are frequent, causing the dust particles to be accelerated and the formation of the observed radicals (Biermann, 1971). The source of the ions for the type I tail has also been traced to an area several thousand kilometers on the sunward side of the nucleus (Rahe, et. al., 1969). Also important is the structure of comet's interaction with the solar wind (Biermann, et. al., 1967). At a distance of 10^4 to 10^5 km, a contact discontinuity between comet plasma and a turbulent mixture of comet and solar wind plasma is expected. A larger volume of the order of several million kilometers radius enclosed within the bow shock contains the hydrogen recently discovered by OGO-5 and OAO-2 as well as the turbulent mixture.

The solar wind and magnetic field cause the shape of the bow shock and contact discontinuity to be parabolic and the direction of the ion tail to be anti-solar. The shape of the dust tail is determined by solar radiation pressure and gravity (Finsen and Probstein, 1968).

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* For records of the appearance of comets at previous apparitions (to 1957) the reader should consult Vsekhsvyatskii (1964) and Comet Notes in the Publications of the Astron. Soc. Pacific by E. Roemer.

FIGURE 2-1 COMET MORPHOLOGY

This photograph of P/Halley 1910 II was taken at Lowell Observatory, Flagstaff, Arizona on May 8, 1910. The comet was 0.71 AU from the sun and 0.52 AU from the earth. A 35-inch Brashear lens was used for the 24 minute exposure.

COMET COMPOSITION AND SPECTRA

What is currently known about comet composition is inferred from spectra. The relative strengths of the prominent lines of identified comet species are given for the four comets which are mission candidates. The species are, however, probably produced by the dissociation of parent molecules which are as yet unidentified. The ionized radicals (CO^+ and N_2^+) are seen only in P/Encke and especially in P/Halley which have plasma tails, while the strong continuum for Halley implies a large amount of dust and a dust tail. A good spectrum of P/Encke was obtained by Swings, et. al. (1957), while those of P/d'Arrest and P/Kopff cover a smaller wavelength band and are less sensitive (White, 1970; Dossin 1965). Extensive analysis of Halley's spectrum, again in a restricted band, was done by Bobrovnikoff (1927 and 1931).

Recent results from OGO-5 and OAO-2 have demonstrated that the two strongest comet emissions are H (Lyman alpha at 122 nm.) and OH (309 nm.) both of which are attenuated by the earth's atmosphere. For this and other reasons water ice is expected to be the major constituent of the comet nucleus. An icy-conglomerate model of the nucleus was first formulated by Whipple (1950 and 1963). Delsemme and Miller (1970) have extended the icy nucleus model to include clathrate-hydrates of gases or an ice lattice with gases (i.e., parent molecules) in crystal cavities. Gas production is then regulated by the sublimation of the ice and the surface area of ice including grains in a halo about the nucleus.

With very high spectral resolution, the lines of many metals (especially Na, Si, Ca and Fe) can be observed in new comets with small perihelia. Unsuccessful efforts have been made in the infrared and microwave spectral regions to find new species, such as those recently discovered in interstellar space.

TABLE 2-2.

COMET SPECTRA

MOLECULAR SPECIES	EMISSION WAVELENGTHS	P/ENCKE	P/d'ARREST	P/KOPFF	P/HALLEY
CN	388 nm	S	S	S	S
C_2	474 516 564	S	M	M	S
C_3	405	S	M	M	M
CH	428	W	W	W	W
NH	336	W	-	-	-
NH_2	630	W	-	-	-
OH	309	W	W	-	-
CO^+	400 426 455	W	-	-	M
N_2^+	391	W	-	-	W
CONTINUUM	-	W	W	W	S

S = STRONG M = MODERATE W = WEAK

COMET BRIGHTNESS

The brightness equations which are given here for the four comets are the same equations used in current ephemerides (Marsden, private communication). By definition the total magnitude includes all coma visible emissions; principally C_2 lines for visual estimates, but primarily CN for panchromatic photographic film. It is a useful indicator of the ease of obtaining simultaneous Earth-based photometric and spectroscopic data. The fact that comet activity is confined to a short interval near perihelion is reflected in the 15 log r term in each total brightness equation. Emission is thus proportional to the -6th power of the solar distance. In reality comet brightness is not so easily predicted. Both Kresak (1965) and Sekanina (1970) agree that Encke is about ten times brighter before perihelion than after (the formula given is based primarily on pre-perihelion data). They also demonstrate that there is a secular decrease in brightness amounting to at least 0.1 magnitudes per revolution. A reading of the observations of d'Arrest and Kopff reveals that the maximum brightness generally occurs at 30 and 15 days after perihelion, respectively. Ad hoc corrections to the brightness equations have not been employed in our work.

For astrometric purposes, the nuclear or condensed magnitude is appropriate since it predicts the brightness of the spot (central condensation or nucleus) whose position is needed for orbit determination. Indeed the nuclear magnitude equation for P/Encke is identical to that for an asteroid of 1.7 km radius and an albedo of 0.10. P/d'Arrest and P/Kopff are slightly larger (using data of E. Roemer in Comet Notes). At a density of $1.0 g/cm^3$, the mass of a 2 km radius comet nucleus would be 3.4×10^{13} kg. From the location and brightness of P/Halley near the time of its recovery in 1909, its radius is estimated to be 20 km.

TABLE 2-3

COMET BRIGHTNESS

TOTAL MAGNITUDE EQUATIONS*	
P/ENCKE	$M_1 = 11.5 + 15 \log r + 5 \log\Delta$
P/d'ARREST	$M_1 = 9.5 + 15 \log r + 5 \log\Delta$
P/KOPFF	$M_1 = 7.0 + 15 \log r + 5 \log\Delta$
P/HALLEY	$M_1 = 4.0 + 15 \log r + 5 \log\Delta$
NUCLEAR MAGNITUDE EQUATION	
P/ENCKE	$M_2 = 15.5 + 5(\log r + \log\Delta) + 0.03\,\Phi$
CONDENSED MAGNITUDE EQUATIONS	
P/d'ARREST	$M_2 = 15.5 + 10 \log r + 5 \log\Delta$
P/KOPFF	$M_2 = 13.5 + 10 \log r + 5 \log\Delta$
P/HALLEY	$M_2 = 8.5 + 10 \log r + 5 \log\Delta$

* r = Solar distance

Δ = Geometric distance

Φ = Phase angle

RECOVERY AND EARTH-BASED OBSERVATIONS

For each of the four candidate comets, the total brightness (M_1) and the nuclear or condensed magnitudes (M_2) have been calculated at 10 day intervals using the brightness equations and orbital elements given previously. Friedlander, et.al. (1970) has graphs of these magnitudes, the nightly observing time and the geocentric distance over a 600 day interval centered on perihelion. The observing times were calculated for latitudes of 35°N (which is plotted) and 35°S with the comet in a dark sky; i.e., the sun was at least 18° below the horizon. Recovery was estimated to occur when the comet was 20th magnitude or brighter for at least one hour per night. Simultaneous Earth-based observations were assumed possible if the comet was in a dark sky and had a total magnitude of 12 or brighter. An early recovery and a good opportunity for simultaneous observations were both used as criteria in selecting the candidate missions.

All four recoveries use northern hemisphere telescopes and are not delayed by short observing times. Observations of P/Encke and P/Halley are interrupted near perihelion when the comets are near superior conjunction and both may require southern hemisphere telescopes for post-perihelion observation. Considering the asymmetry in the activity of P/Encke the absence of observations after perihelion in 1980 does not make that apparition inferior to 1984. Minimum arrival dates of 50 days before perihelion were established for P/Encke and P/Halley and 25 days before for P/d'Arrest and P/Kopff based on the opportunities for simultaneous observation and expected activity. A mission duration of at least 80 days is required to cover the period of major comet activity and to carry out a spatial investigation of the coma. If the mission can be extended to one year after rendezvous then measurements can be made when the comet-sun distance is over 3.0 AU or when comet activity has ceased.

TABLE 2-4

SUMMARY OF RECOVERY AND EARTH-BASED OBSERVATIONS

COMET/YEAR	RECOVERY, DAYS AFTER T_p	NUCLEAR BRIGHTNESS, M_2	OBSERVING TIME, HOURS/DAY
ENCKE/80	-150	20.0	2.0
d'ARREST/82	-170	20.0	5.6
KOPFF/83	-220	19.6	3.4
ENCKE/84	-220	20.0	5.5
HALLEY/86	-400	18.8	5.8

COMET/YEAR	EARTH-BASED OBSERVATION TIME, DAYS AFTER T_p	MAXIMUM BRIGHTNESS, M_1	MINIMUM DISTANCE, AU
ENCKE/80	- 60 to - 20	7.5	0.26
d'ARREST/82	- 80 to 50	10.6	0.73
KOPFF/83	-130 to 80	9.8	0.78
ENCKE/84	- 40 to - 20 20 to 50	8.6 7.5	1.18 0.73
HALLEY/86	-140 to - 30 30 to 140	3.7 3.2	0.61 0.46

SCIENCE QUESTIONS FOR COMET MISSIONS

Determining the origin and evolution and understanding the perihelion activity are the two major goals of comet exploration. The list of pertinent questions which are related to these goals will be useful in selecting science instruments for comet missions.

Information about the origin of comets can be obtained by investigating the nucleus which is thought to be a small body, the source of cometary activity, and the only permanent part of a comet. In particular, the size, shape, physical state and especially the composition of the nucleus should be determined. Also important are studies of processes which are responsible for the evolution of the comet. At perihelion the volitization of the nucleus by solar heating is probably the dominant process while at aphelion the important processes are those that would affect a new comet while it is very far from the sun such as surface errosion caused by energetic particles and micrometeorites. Since these questions are indirect, answers to them may not lead to a unique explanation of comet origin.

The value of previous and future comet observations will be enhanced by the study of comet activity near perihelion. Observations of molecules, ions and solid particles are needed to find their spatial density as a function of heliocentric distance. This includes determining the source of the observed molecules and ions and the nature of the interaction between the comet and the solar wind. The relationship between activity and what is happening to the nucleus should also be studied.

TABLE 2-5

SCIENCE QUESTIONS FOR COMET MISSIONS

QUESTIONS RELATED TO ORIGIN AND EVOLUTION OF COMETS

- WHAT IS THE COMET NUCLEUS LIKE?
- WHAT HAPPENS TO THE NUCLEUS AT PERIHELION?
- WHAT HAPPENS TO THE NUCLEUS AT APHELION?
- WHAT IS THE COMPOSITION OF THE PARENT MOLECULES?
- WHAT IS THE COMPOSITION OF THE DUST PARTICLES?
- WHAT NON-GRAVITATIONAL FORCES ACT ON THE NUCLEUS?

QUESTIONS RELATED TO OBSERVED COMET ACTIVITY

- HOW ARE MOLECULES AND IONS FORMED?
- HOW ARE THE MOLECULES AND IONS DISTRIBUTED IN SPACE?
- HOW DOES THE COMET INTERACT WITH THE SOLAR WIND?
- HOW LARGE ARE THE SOLID PARTICLES?
- WHAT CAUSES SUDDEN CHANGES IN COMET ACTIVITY?

PROPOSED SPATIAL INVESTIGATION DURING RENDEZVOUS

One of the unique features of a comet rendezvous mission is the opportunity to choose areas for spatial investigation. With a flythrough, the only variables are the miss distance and the angle. The design of one possible stationkeeping plan which fulfills some specific scientific objectives is presented here. Any stationkeeping program must be flexible so that it can be altered to better fulfill the scientific objectives of the mission or to prevent the spacecraft from being exposed to severe environmental conditions. On-board decision making would be useful for making these changes but is probably not necessary since the communications delay will not be more than a half hour.

An objective was to provide reconnaissance of the nucleus both before and after perihelion so that changes might be observed. For this purpose the plan includes two circumnavigations of the nucleus at a distance of about 100 km to obtain remote sensing data on the nucleus both before and after perihelion. To investigate the radial structure of the coma a traverse of approximately 20,000 km is made toward the sun. The spacecraft then enters the region of free molecular flow (outer coma) and explores the region where the ion tail streamers originate. This is followed by a longer traverse that ends at a point some 20,000 km from the nucleus in the anti-solar direction. Ten days are spent there observing the temporal behavior of the plasma tail. On the return path to the nucleus the dust tail is studied.

The nominal schedules given here are based on the expected periods of comet activity and on the availability of simultaneous Earth-based observations. The stationkeeping process takes about 80 days and involves relative velocities of 20 m/sec or less. The total ΔV requirement is less than 200 m/sec.

TABLE 2-6

PROPOSED SPATIAL INVESTIGATIONS DURING RENDEZVOUS

EVENT*	TIME OF COMPLETION, DAYS AFTER T_p			
	ENCKE	d'ARREST	KOPFF	HALLEY
ARRIVAL	-50	-25	-25	-50
1	-40	-15	-15	-30
2	-30	0	0	-10
3	-10	30	30	30
4	0	40	40	50
5	20	55	55	70
1	30	65	65	80

* 1 CIRCUMNAVIGATION OF NUCLEUS

2 RADIAL TRAVERSE TOWARD SUN

3 RADIAL TRAVERSE AWAY FROM SUN

4 STATIONKEEPING IN TAIL REGION

5 RETURN TO NUCLEUS

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3. SCIENCE INSTRUMENTS

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SECTION 3 SUMMARY

A nominal science instrument package is selected from currently available or proposed devices. Visual imagery of the nucleus, its photometric properties and its temperature will be obtained by the science TV and the photometer/radiometer during the circumnavigations. In-situ data from the surface of the nucleus can be collected by a deployed probe which has temperature, pressure and α-scattering detectors and accelerometers.

For the exploration of the coma, the remote sensing and in-situ instruments are complimentary. The later measures the cometary properties near the spacecraft while the former determines conditions at other locations. The UV, V spectrometer and the mass spectrometer both measure the abundances of molecules and ions and the photometer/radiometer and the solid particle detector both determine the extent of dust in the coma. The other in-situ instruments, the magnetometer, the plasma analyzer and the plasma wave detector, are included to study the interaction between the comet and the solar wind. Two additional instruments to measure the composition of solid particles and of energetic ions need to be developed for comet rendezvous missions. The total weight of the science instruments, the maximum power and maximum data rate are estimated to be 70 kg, 90 w and 2.6 x 10^8 bits per day respectively.

INSTRUMENT USE FOR COMET MISSIONS

The science questions are repeated on the left of this figure and an "X" is used to indicate what candidate instruments will contribute useful data for answering the questions. In most cases both remote sensing instruments (TV, spectrometers, photometer/radiometer) and in-situ instruments are needed. The two instrument types are complimentary in that the in-situ instruments are used to calibrate the remote sensing devices and thus the value of both spacecraft and Earth-based remote sensing data is enhanced. Since they measure one point at a time, the in-situ instruments do not provide the desired spatial information. Correlation of rendezvous data with Earth-based observations is important because it aids interpretation of the observations of past and future comets.

One set of complimentary instruments is the mass spectrometer and the UV, V and IR spectrometers. The latter record the resonance fluorescence line emissions while the former measures the masses of comet molecules and ions. The spatial distribution of dust particles is obtained with the photometer/radiometer, while the density and composition of the particles is measured with in-situ detectors on the spacecraft. For investigation of the nucleus, only remote sensing instruments are considered here. The rationale for a nucleus probe to conduct in-situ measurements of the nucleus is presented in the next figure.

FIGURE 2-1 INSTRUMENT USE FOR COMET RENDEZVOUS MISSIONS

QUESTIONS \ INSTRUMENTS	SCIENCE TV	UV, V SPECTROMETER	PHOTOMETER/RADIOMETER	MASS SPECTROMETER	SOLID PARTICLE DETECTOR	PLASMA ANALYZER	MAGNETOMETER	PLASMA WAVE DETECTOR	RADIO TRACKING
WHAT IS THE COMET NUCLEUS LIKE?	X		X						
WHAT HAPPENS TO THE NUCLEUS AT PERIHELION?	X		X	X	X				
WHAT HAPPENS TO THE NUCLEUS AT APHELION?	X		X						
WHAT IS THE COMPOSITION OF THE PARENT MOLECULES?				X					
WHAT IS THE COMPOSITION OF THE DUST PARTICLES?					X				
WHAT NON-GRAVITATIONAL FORCES ACT ON THE NUCLEUS?									X
HOW ARE MOLECULES AND IONS FORMED?		X		X		X			
HOW ARE MOLECULES AND IONS DISTRIBUTED IN SPACE?		X		X		X			
HOW DOES THE COMET INTERACT WITH THE SOLAR WIND?						X	X	X	
HOW LARGE ARE THE SOLID PARTICLES?			X		X				
WHAT CAUSES SUDDEN CHANGES IN COMET ACTIVITY?		X		X		X	X	X	

RATIONALE FOR A NUCLEUS PROBE

There are two ways in which in-situ measurements can be made on the surface of the comet nucleus. A small nucleus probe can be deployed from the main spacecraft or the entire spacecraft can dock with the nucleus. The quality of measurements and mission complexity have been rated for four possible mission concepts. While the docking concept would allow the use of more sophisticated instruments, the spacecraft cannot remain on the nucleus for long without causing a decrease in the value of measurements made in the coma. Because of the uncertainty about the environment near and on the nucleus and the difficulty of performing the docking maneuver, the nucleus probe concept is less complex and therefore the preferred mode for in-situ nucleus exploration.

What if there is no solid nucleus? The probe would then provide data on what makes up the photometric center of the comet. While the duration of measurements may be short in this case, this method obtains the data with little hazard to the rendezvous spacecraft. Instruments for the probe are discussed in Table 3-6.

FIGURE 3-2

RATIONALE FOR A NUCLEUS PROBE

		RENDEZVOUS MISSION CONCEPTS			
		WITHOUT PROBE	WITH PROBE	SHORT DOCKING	LONG DOCKING
MEASUREMENT RATINGS	REMOTE COMA	GOOD	GOOD	GOOD	FAIR
	IN-SITU COMA	GOOD	GOOD	GOOD	POOR
	REMOTE NUCLEUS	FAIR	FAIR	FAIR	FAIR
	IN-SITU NUCLEUS	-	FAIR	POOR	GOOD
MISSION COMPLEXITY		LOW	MEDIUM	HIGH	HIGH

THE APPROACH ACQUISITION AND SCIENCE TV SYSTEMS

There are two uses for visual imagery during a comet rendezvous mission. The uncertainty in the position of the comet during the approach phase can be reduced by locating the nucleus relative to background stars. The comet can be acquired when it is 9th magnitude with a slow scan vidicon similar to that used on Mariner 9 if collecting optics are 20 cm in diameter, the focal ratio is 0.75 and the exposure time is about 10 seconds (Gardner, 1971). Data compression can be used to reduce the data load to about 250 bits per frame by transmitting the coordinates and brightness of significant spots. With this system the uncertainty in the location of the nucleus is about 10 km at rendezvous. Using only Earth-based optical tracking results in an uncertainty of several thousand kilometers (see Figure 6-5). While this system is adequate for approach acquisition, other systems should be investigated in subsequent studies to determine the optimum solution to the approach guidance problem.

Visual imagery of the nucleus is desired to determine its size, shape and surface morphology. Because there are no established scientific requirements for imagery, the system described here was designed to give full disc images of a 2 km radius nucleus at a range of 100 km. Thus during the circumnavigations of the nucleus, a surface resolution of 10 m will be achieved by a Mariner slow scan vidicon with a focal length of 30 cm. A 5 cm diameter lens is five times the diffraction limit giving a focal ratio of 6 and a minimum exposure time of 4 msec. The smaller optics accounts for the lighter weight of this TV. The data rate is based on 30 frames per day with 6×10^6 bits per frame. A tape recorder which can accept data at the rate of 10^5 bits per second will be used. While this Science TV dominates the data collected during the nucleus circumnavigations, it is a reasonable estimate of what can be accomplished during a rendezvous mission.

TABLE 3-1

THE APPROACH ACQUISITION AND SCIENCE TV SYSTEMS

	APPROACH ACQUISITION	SCIENCE
OBJECTIVE	RECOVERY AT 9TH MAGNITUDE	IMAGERY WITH 10m RESOLUTION
SENSOR TYPE	SLOW SCAN VIDICON	SLOW SCAN VIDICON
FOCAL LENGTH	15 cm	30 cm
FIELD OF VIEW	4°x4.8°	2°x2.4°
SYSTEM ANGULAR RESOLUTION (MTF=0.1)	-	10^{-4} radians
RESOLUTION PER TV LINE	4.8×10^{-5} radians	2.4×10^{-5} radians
LENS DIAMETER	20 cm	5 cm
APERTURE STOP (f#)	0.75	6
EXPOSURE TIME	10 sec.	4 m sec.
BITS PER FRAME	6×10^{6}	6×10^{6}
FRAME READOUT TIME	60 sec.	60 sec.
READOUT RATE	100 kbps	100 kbps
MEASUREMENTS PER DAY	4	50
DATA LOAD PER DAY	2.4×10^{6} bits	1.8×10^{8} bits
WEIGHT	18 kg	12 kg
POWER	25 w	25 w

UV, V SPECTROMETER AND PHOTOMETER/RADIOMETER

One spectrometer cannot cover the entire range of cometary emissions. Thus priority was given to a UV, V spectrometer operating between 1100 and 5000 Å with approximately 20 Å spectral resolution. This should be adequate to map the spatial distribution of most known species (see Table 2-2), and allows a search for new species in the far ultraviolet. For a 2° FOV the lens diameter can be less than 10 cm. The weight given in Table 3-2 is based on the Mariner Venus/Mercury instrument, a concave grating spectrometer with channeltron detectors, with the addition of a scanning capability and several photometers for measuring hydrogen (1216 Å) and helium (304 and 584 Å) lines. Spectroscopy in the infrared has been proposed only for discovering molecular absorption bands which would appear when the instrument looks directly at the sun through the inner coma.

The photometer/radiometer combination has a common purpose although separate optics may be required. Each should have a 2° FOV which would be filled by a 2.0 km radius nucleus at a range of 100 km. This angular resolution is also useful for determining the spatial distribution of particles in the coma. Since the photometer is measuring reflected light, the bands must be chosen carefully to exclude as much line emission as possible. Capability to measure polarization is also desirable. The infrared radiometer needs several channels in the 5 to 50 μm region to determine temperatures from about 100°K (nucleus) to 1000°K (coma particles at 0.3 AU). Assuming that a phototube is used for the photometer and a thermistor bolometer for the radiometer, the optics required are 5 cm or less in diameter and thus these instruments will weigh about the same as similar ones on Pioneer F/G.

TABLE 3-2

UV, V SPECTROMETERS AND PHOTOMETER/RADIOMETER

	UV, V SPECTROMETER	PHOTOMETER/ RADIOMETER
OBJECTIVE	MEASURE COMET EMISSION LINES	MEASURE REFLECTED & EMITTED ENERGY
SENSOR TYPE	CONCAVE GRATING AND CHANNELTRON DETECTORS	PHOTOTUBE/ THERMISTOR
SPECTRAL RANGE	1100-5000 Å AND 304,584,1216 Å LINES	3000-8000 Å / 5-65 μm
SPECTRAL RESOLUTION	20 Å	100 Å/20 μm
DATA PER MEASUREMENT	2,000 bits	100 bits
MEASUREMENTS PER DAY	5,000	10^5
DATA LOAD PER DAY	10^7 bits	10^7 bits
FIELD OF VIEW	2°	2°
LENS DIAMETER	10 cm	5 cm
WEIGHT	6 kg	6 kg
POWER	10 w	10 w

D

MASS SPECTROMETER

The mass spectrometer measures the composition of the neutral gas in the coma. A collision free design is preferred to prevent the dissociation of molecules or recombination of radicals in the instrument. The dual range double focusing mass spectrometer developed for Viking entry is adequate (Nier and Hayden, 1971). It should have pointing capability. The mass range of 1-60 AMU includes all identified species, the rare gases (helium, neon and argon), and the recently discovered interstellar molecules (the heaviest being OCS - mass 60. The dynamic range estimate is based on a range of gas densities from 10^3 to 10^9 cm^{-3}.

A mass analysis of coma ions and solid particles is also desired. If the ion velocity is 50 km/sec or less they can be studied when the ionizing mechanism of the mass spectrometer is turned off. Higher velocities are a problem unless all particles have approximately the same velocity, in which case the plasma detectors will determine the composition. The composition of the volatiles in the particles can be determined with the neutral mass spectrometer if particles can be vaporized. A composition detector for the dust component is not currently available. Many techniques such as an X-ray fluorescence spectrometer or an ion microprobe could be used if a large enough sample could be collected.

TABLE 3-3

MASS SPECTROMETER

OBJECTIVE	DETERMINE COMPOSITION OF COMET MOLECULES, IONS
SENSOR TYPE	DOUBLE FOCUSING MASS SPECTROMETER WITH COLLISION FREE APERTURE
MASS RANGE	1-8 AND 8-60 AMU
RESOLUTION	1 AMU
DYNAMIC RANGE	$1\text{-}10^6$ particles/sec
SAMPLE RATE	0.1 sec
DATA PER SAMPLE	20 bits
DATA PER DAY	2×10^7 bits
WEIGHT	7 kg
POWER	15 w

FIELDS AND PARTICLES INSTRUMENTS

The size and velocity of particles, both dust and ice, are determined by an optical particle detector also known as the Sisyphus detector which is a Pioneer F/G experiment. The same principles, measuring the position and brightness of a particle as a function of time, can be used with imagery although the data rate would be greater, but the ambiguity less if several particles are in the field of view. Some size information may come from photometry and polarimetry. Other commonly used detectors, including an impact mass spectrometer depend on high (> 1 km/sec) impact velocities.

Five or more electrostatic plasma analyzers are required to obtain the energy per unit charge of both electrons and ions, one set covering the range 10V to 10 kV, the others 3-50 kV. The latter instrument is also known as the LEPEDEA. In addition the pitch angle distribution with respect to the local magnetic field is to be determined. If the majority of ions have the same velocity, then this measurement of E/q can be converted to a composition (M/q) data. A tri-axial fluxgate magnetometer measures the steady component of the magnetic field which would be compared to the solar field of several gammas. Also of some interest is the higher frequency components (10 Hz to 100 kHz) of the electric and magnetic fields measured with dipole and search coil detectors respectively. These fields and particles experiments are similar to ones used in Earth orbit and to the proposed Grand Tour instruments.

TABLE 3-4

FIELDS AND PARTICLES INSTRUMENTS

SOLID PARTICLE DETECTOR

SISYPHUS DETECTOR MEASURES SIZE, VELOCITY OF PARTICLES (>1μ) NEAR SPACECRAFT.

WEIGHT, 3 kg; POWER 3 w;

DATA PER DAY, 3×10^5 bits (10^4 events @ 30 bits each)

PLASMA ANALYZER

ELECTROSTATIC PLASMA ANALYZERS MEASURE ENERGY SPECTRUM AND PITCH ANGLE DISTRIBUTION OF IONS, ELECTRONS.

ENERGY RANGES: 10 V–10 kV and 3-50 kV.

WEIGHT, 5 kg; POWER, 7 w;

DATA PER DAY, 10^7 bits (2×10^5 samples @ 50 bits each)

MAGNETOMETER

TRI-AXIAL FLUXGATE MAGNETOMETER MEASURES DIRECTION AND MAGNITUDE OF LOCAL MAGNETIC FIELD.

SENSITIVITY, 0.18; FREQUENCY RANGE, D.C. TO 10 Hz.

WEIGHT, 3 kg; POWER, 5 w;

DATA PER DAY, 3×10^6 bits (10^5 samples @ 30 bits each)

PLASMA WAVE DETECTOR

DIPOLE AND SEARCH COIL DETECTORS MEASURE E AND B WAVES FROM 10 Hz to 100 kHz

WEIGHT, 3 kg; POWER, 5w;

DATA PER DAY, 3×10^6 bits (10^5 samples @ 20 bits each)

COMET RENDEZVOUS SCIENCE PAYLOAD

The weight and power of the instruments were taken from current technology, primarily Mariner Mars '71, Pioneer F/G and the Grand Tour. For all the remote sensing instruments, the size of the collecting optics was determined and an appropriate allowance made in the case of the approach acquisition TV, when a 20 cm diameter lens was required. The remote sensing instruments, the mass spectrometer and the plasma analyzer should all be located on a scan platform. A payload of 70 kg (and a power of 90 watts) is used in subsequent spacecraft subsystem analysis allowing about 10% for growth in the science instrument package. Additional consideration should be given to developing a solid particle composition detector and an energetic ion composition analyzer which could be added to this list.

The data rate has been calculated on a bits per day basis. The estimated 30 science TV frames per day dominate the data rate, but only during the time when the spacecraft is near (within several hundred kilometers) the nucleus. Compression of the approach acquisition TV data into the coordinates and brightness of significant spots was assumed. However, about 4 frames per day of uncompressed data is all that would be required. Approximately one hundred UV, V spectra, ten thousand mass spectra and ten thousand plasma energy spectra are provided each day. Several emission lines, the reflected solar continuum, and thermal IR emission can be mapped over 4 π sterradians about 100 times per day.

TABLE 3-5

COMET RENDEZVOUS SCIENCE PAYLOAD

INSTRUMENT	WEIGHT	POWER	DATA[a]
APPROACH ACQUISITION TV	18 kg	25 w	10^3 bpd
SCIENCE TV	12	25	2×10^8
UV, V SPECTROMETER	6	10	10^7
PHOTOMETER/RADIOMETER	6	10	10^7
MASS SPECTROMETER	7	15	2×10^7
SOLID PARTICLE DETECTOR	3	3	3×10^5
PLASMA ANALYZER	5	7	10^7
MAGNETOMETER	3	5	3×10^6
PLASMA WAVE DETECTOR	3	5	2×10^6
CONTINGENCY	7	10	
TOTAL	70 kg	90 w[b]	2.6×10^8 bpd[c]

a. ESTIMATED DATA PER DAY

b. ONLY ONE TV IN USE AT ANY TIME

c. ABOUT 6×10^7 bpd WITHOUT SCIENCE TV

INSTRUMENTS FOR A NUCLEUS PROBE

Since the proposed nucleus probe will be a small one (about 60 kg), the instrumentation must be small and simple. Three such instruments are an accelerometer, a temperature sensor and a pressure gauge. The strength of the surface of the comet nucleus will be determined by the accelerometer response to the probe's impact. This data will be useful for the design of docking mechanisms for subsequent missions. The temperature and pressure data can be used to independently estimate the rate at which molecules leave the surface of the nucleus.

An instrument to measure the abundances of the major elements is also desired. Alpha particle backscattering, mass spectroscopy, x-ray fluorescence and neutron capture gamma ray spectroscopy are candidate techniques. Since the nucleus is expected to have hydrogen, carbon and oxygen in abundance, a technique sensitive to these elements is preferred. This eliminates the x-ray experiment. Although the sensitivity of the α-scattering detector to hydrogen is unknown, it is included in the payload since it is the simplest and best developed instrument. When current development programs are complete, it may be possible to substitute one of the other techniques.

TABLE 3-6

INSTRUMENTS FOR A NUCLEUS PROBE

ACCELEROMETER

MEASURES DECELERATION DURING IMPACT

WEIGHT, 1 kg; POWER, 1 w

TEMPERATURE PROBE

DETERMINES SURFACE TEMPERATURE

MEASUREMENT RANGE: 75-150°K

SENSITIVITY: 1°K

WEIGHT, 0.5 kg; POWER, 0.5 w

PRESSURE GAUGE

DETERMINES TOTAL GAS PRESSURE AT NUCLEUS SURFACE

MEASUREMENT RANGE: 10^{-9} to 10^{-5} bars

WEIGHT, 0.5 kg; POWER, 0.5 w

ALPHA-SCATTERING EXPERIMENT

MEASURES ABUNDANCE OF MAJOR ELEMENTS

WEIGHT, 5 kg; POWER, 7 w.

4. SPACECRAFT DEFINITION

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SECTION 4 SUMMARY

The spacecraft is sized using subsystem scaling laws to meet the requirements imposed by the science instruments and by the mission. The instruments establish a data transmission rate of 4.0 kbps and the data storage capacity. Science accounts for 14% of the estimated spacecraft mass (70 out of 500 kg) and for 36% of the power consumption (90 out of 250 w). Three mission requirements are used in the estimating procedures. They are: operation of the spacecraft at full power and data rate at distances of 2.0 AU, a propulsion capability of 200 m/sec for midcourse and stationkeeping maneuvers, and the ability to operate for two hours on battery power.

The effects of the comet meteoroid environment are uncertain. For a nominal model 10 kg of meteroid protection placed on the spacecraft should be sufficient. No problems with radio communications are anticipated from either the comet or the sun. When operating near the nucleus, the spacecraft attitude must be determined by a device that is not affected by a high level of background illumination.

Overall the differences in net mass between a ballistic spacecraft and an integrated SEP spacecraft are small. The SEP system should not be jettisoned at rendezvous. A multi-mission SEP spacecraft can probably be used for comet rendezvous.

POTENTIAL ENVIRONMENTAL PROBLEMS

A worst case model for the meteroid environment in a comet coma was developed for the comet d'Arrest Mission Study (Gardner, 1971). It is based on an assumed particle density of 70 m^{-3} at 1500 km from the nucleus with mass greater than 10^{-12} grams. This is more than 100 times greater than the particle density observed by Mianes, et. al. (1960) in P/Encke and P/Giacobini-Zinner. The nominal model also differs from the worst case in the particle mass distribution used to extrapolate between 10^{-12} grams and 10^{-6} grams (for $m > 10^{-6}$ grams the models use similar mass laws). The difference in the two models also shows up in a calculation of the probability of hits. Under conditions approximating our near nucleus operations the nominal model says that the probability of a hit by a particle larger than 0.02 g is less than 5%. But for the worst case model this increases to about a 6 kg particle! If further study shows that such a worst case model is appropriate, then a precursor flythrough measurement would be helpful in assessing the problem.

The number of molecules or ions in the comet along a line-of-sight to the nucleus is smaller than the sum of interplanetary space (over 1 AU) and the Earth's atmosphere. Thus no problems are anticipated with radio transmission. In all four cases the comets remain at least 6° away from the sun, so solar interference (which is a problem at 2°) is not expected.

Many star trackers have a field of view of about 1° by 10°. With such a large FOV the light from the coma can exceed the contribution of Canopus. Either a smaller effective FOV tracker or an alternate method of determining the spacecraft altitude will be needed during operations near the nucleus.

TABLE 4-1

POTENTIAL ENVIRONMENTAL PROBLEMS

- METEOROIDS

NOMINAL MODEL (THIS STUDY)

$N(>m, S, r) = 5.3 \times 10^{-9}\ m^{-1.2}\ S^{-2}\ r^{-4}$

for $m > 10^{-12}$ grams

WORST CASE MODEL (JPL d'ARREST STUDY)

$N(>m, S) = 1.7 \times 10^{-2}\ m^{-1.213}\ S^{-2}$

for $m > 10^{-6}$ grams

WHERE

$N(>m, S, r)$ IS SPATIAL DENSITY OF SOLID PARTICLES PER m^3 WITH MASS LARGER THAN m.

S IS DISTANCE FROM NUCLEUS IN km.

r IS DISTANCE FROM SUN IN AU.

PROTECTION OF SPACECRAFT NOT A PROBLEM FOR A "NOMINAL" MODEL ENVIRONMENT, BUT "WORST CASE" MODEL WOULD LIMIT OPERATIONS.

- RADIO COMMUNICATIONS

NO SPECIAL PROBLEMS WERE FOUND WITH EITHER THE COMET ENVIRONMENT OR SOLAR INTERFERENCE.

- ATTITUDE CONTROL

STAR TRACKER MUST HAVE SMALL FIELD OF VIEW.

COMET RENDEZVOUS SPACECRAFT SUBSYSTEM CAPABILITIES

For this study, the sizes of spacecraft subsystems were determined by a scaling law analysis. These scaling laws were developed at IITRI (Klopp and Wells, 1971) using in some cases formulations by Kennet and Spear (1969) and Edsinger (1971). They are based on previous experience with designs of spacecraft, such as Mariner and Lunar Orbiter. One set of desired capabilities was established so that the proposed spacecraft could be used for any of the four comets in this study. Both a ballistic and an integrated solar electric spacecraft are sized. Jettisoned spacecraft and multi-mission SEP spacecraft are also considered.

A basic set of inputs to the scaling analysis are the weight (70 kg) power (90 w) and data rate of the science instruments. The maximum data load of 2.6×10^8 bits per day requires a data transmission rate of at least 4.0 kbps. This rate should be possible with a communications distance of 2.0 AU. The data storage requirement is one day's data.

Power for the spacecraft should be available to a solar distance of 2.0 AU. Thus solar cells are the obvious choice. A battery is needed to provide a 2 hour reserve. Since only a few discharge cycles are anticipated, including earth occultation following launch, silver-zinc cells are used. A ΔV capability of 200 m/sec is needed for midcourse guidance and stationkeeping maneuvers during rendezvous.

TABLE 4-2

COMET RENDEZVOUS SPACECRAFT
SUBSYSTEM CAPABILITIES

SUBSYSTEM	CAPABILITY
COMMUNICATIONS	4 kbps AT 2 AU 20 w TRANSMITTER
ANTENNA	2.5 m DISH
DATA STORAGE	TWO RECORDERS, 4×10^8 BITS
POWER SUPPLY	250 w AT 2 AU (SOLAR CELLS)
BATTERY	500 w-hr, AgZn
PROPULSION	200 m/sec

ε

COMET RENDEZVOUS SPACECRAFT MODELS

Assuming that the 64 meter DSN antenna is used for data reception, the required data rate of 4.0 kbps can be accomplished using a 20 watt S-band transmitter and a 2.5 meter parabolic antenna. A redundant 20w TWT is provided for in the 28 kg estimate of the communications subsystem weight. Data storage is provided by two Mariner tape recorders.

Differences between ballistic and SEP spacecraft appear in the next three subsystems. The computer/sequencer weight is estimated as a fraction of total spacecraft weight. However for an SEP mission additional capacity will be required to handle commands to and data from the powerplant. Because of the larger moments of inertia of a SEP system it is estimated that the reaction control part of the attitude control system will be 10 kg greater than for the ballistic mission. The attitude control subsystem weight also includes the attitude reference sensors and logic. The power requirement is approximately 250w. The SEP spacecraft gets free power from its large solar array, but it was assumed that it would still require its own power conditioning and battery.

Protection of vital spacecraft components from the nominal meteoroid flux is possible with about 10 kg of shielding. A more severe environment would require more shielding or a different operations schedule. The cabling, thermal control and structure are all estimated as fractions of total spacecraft weight. Structure was included in the SEP integrated spacecraft because engineering studies have included it (TRW, 1971; JPL, 1971).

The basic spacecraft each weigh 365 kg. A chemical propulsion system is used on the ballistic spacecraft but only mercury propellant is required for the SEP mission. There is a contingency allowance and provision for a nucleus probe in the nominal net mass of 500 kg for the ballistic case and 470 kg for the integrated SEP spacecraft.

TABLE 4-3

COMET RENDEZVOUS SPACECRAFT MODELS

SPACECRAFT SUBSYSTEM	BALLISTIC SPACECRAFT	SOLAR ELECTRIC SPACECRAFT
SCIENCE INSTRUMENTS	70 kg	70 kg
SCAN PLATFORM	15	15
COMMUNICATIONS	28	28
ANTENNA	12	12
DATA STORAGE	14	14
COMPUTER/SEQUENCER	15	20
ATTITUDE CONTROL	45	55
POWER SUPPLY	15	-
BATTERY	10	10
POWER CONDITIONING	11	11
CABLING	20	20
THERMAL CONTROL	12	12
METEOROID PROTECTION	10	10
STRUCTURE	88	88
SUBTOTAL	365 kg	365 kg
10% CONTINGENCY	40	40
PROPULSION	35	5
PROBE	60	60
TOTAL	500 kg	470 kg

COMPARISON OF SOLAR ELECTRIC OPTIONS

The differences between the jettisoned and integrated mode of using SEP are shown. The advantages of the integrated option is the lower net spacecraft mass required.

The jettisoned spacecraft (same as the ballistic spacecraft) is about 30 kg heavier than the integrated. In addition, some subsystems of the SEP stage used for the jettisoned mission must be charged against net spacecraft mass. At a bare minimum a staging adapter (25 kg), a command and data multiplexer (5 kg) and a separate reaction control assembly (20 kg) must be included on the SEP stage.

The disadvantages of the integrated mode appear acceptable. They are somewhat longer maneuver execution times, a more severe environment for the SEP subsystems and potential interference between the SEP thrusters and the science instruments.

TABLE 4-4

COMPARISON OF SOLAR ELECTRIC OPTIONS

JETTISONED	INTEGRATED
• SEPARATE SPACECRAFT FROM SEP STAGE AT RENDEZVOUS	• KEEP PROPULSION SYSTEM AFTER RENDEZVOUS
• STATIONKEEPING MANEUVERS PERFORMED BY CHEMICAL PROPULSION SYSTEM	• USE SEP FOR STATIONKEEPING MANEUVERS
• EACH MANEUVER TAKES ~ 1 HOUR	• MANEUVERS TAKE ~ 1 DAY AND REQUIRE DIFFERENT THRUST DIRECTIONS
• PAYLOAD INCLUDES SUBSYSTEMS FOR SEP STAGE SUCH AS COMMAND AND DATA MULTIPLEXER, REACTION CONTROL ASSEMBLY AND STAGING ADAPTER	• SEP SUBSYSTEMS MUST WITHSTAND COMET ENVIRONMENT INCLUDING MICROMETEORITES, SOLAR HEATING, ETC.
• NET SPACECRAFT MASS REQUIRED IS AT LEAST 80 kg MORE THAN INTEGRATED	• SEP INTERFERENCE WITH SCIENCE INSTRUMENTS MUST BE MINIMIZED.

COMET RENDEZVOUS USING A SEP MULTI-MISSION STAGE

Comet rendezvous has been considered in most SEP multi-mission studies. As a result of this study, it is felt that the multi-mission concept can be used for comet rendezvous. There is however, a weight penalty associated with the excess capability of the multi-mission concept, this capability being necessary for other missions.

The penalty has been estimated as 90 kg. The TRW (1971) multi-mission stage using a 15 kw powerplant had a net spacecraft mass of 620 kg, 400 kg of support subsystems and 220 kg of payload capability. Adding together the science instruments, scan platform, meteoroid protection, stationkeeping propellant and nucleus probe, we find that comet rendezvous requires 160 kg of payload. The total is then 560 kg or 90 kg more than the single mission model developed with scaling laws earlier.

A logical part of the multi-mission design would be a longer thruster operating lifetime. Thus the weight penalty for using a multi-mission concept could be paid for by longer thruster on-times.

TABLE 4-5

COMET RENDEZVOUS USING A SEP MULTI-MISSION STAGE

- THE MULTI MISSION STAGE WILL PROBABLY HAVE EXCESS SYSTEMS CAPABILITY FOR COMET RENDEZVOUS.
- USING THE TRW 15 kw STAGE GIVES A REQUIRED NET SPACECRAFT MASS OF 560 kg FOR AN INTEGRATED MISSION CONCEPT.
- MULTI-MISSION STAGE SHOULD HAVE ADDITIONAL PERFORMANCE (PROPULSION ON TIME) TO MAKE UP THE DIFFERENCE BETWEEN THE SINGLE AND MULTI-MISSION CONCEPTS (ABOUT 90 kg).
- A JETTISONED SPACECRAFT FOR COMET RENDEZVOUS WOULD CAUSE TOO MUCH DUPLICATION OF SUBSYSTEMS TO BE PRACTICAL.

COMET NUCLEUS PROBE

The total weight and subsystem breakdown for the nucleus probe was estimated using previous studies for hard landers deployed on the Moon and Mars. The weight allocated to science instruments is 7 kg. Communications performance is about 6 kbps using one watt of transmitted power with an omni antenna. The receiver is on the rendezvous spacecraft and uses the 2.5 m dish. For the probe to have a lifetime of more than a few days the power source will have to be an RTG or solar cells and battery. Ten watts is the estimated demand.

The structure allocation includes items like mechanical devices for leveling and pyrotechnics. The limiters, made of balsa wood, should protect the probe during a 60 m/sec impact. The adapter is on the rendezvous spacecraft and holds the probe before deployment.

TABLE 4-6

COMET NUCLEUS PROBE

SCIENCE	7kg
ACCELEROMETER	
TEMPERATURE GAUGE	
PRESSURE GAUGE	
α-SCATTERING	
COMMUNICATIONS	4
DATA HANDLING, STORAGE	4
COMPUTER / SEQUENCER	2
POWER	5
STRUCTURE	9
LIMITER	14
SUBTOTAL	45 kg
CONTINGENCY	10
ADAPTER	5
TOTAL	60 kg

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SECTION 5: TRAJECTORY/PAYLOAD ANALYSIS

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SECTION 5 SUMMARY

Rendezvous missions to the short-period comets Encke, d'Arrest and Kopff can be accomplished with solar electric propulsion or ballistic (chemical propulsion) systems launched by Titan/Centaur vehicles. The ballistic flight mode requires a high-energy upper stage (Isp $\approx$ 400 sec) and has a marginal payload capability even with the 7-segment Titan needed for the Encke and d'Arrest missions. In comparison, solar electric propulsion has far greater performance potential in terms of significantly shorter flight times and greater payload margins. Using the programmed Titan 3D/Centaur and a 15 kw SEP powerplant, the flight time to d'Arrest and Kopff is only 2 years. Flight time to Encke is 2.6 years (1980 apparition), but can be reduced to 2 years if the mission is delayed to the 1984 apparition.

The essential design tradeoffs of the SEP missions are described. Parameters of interest are arrival time relative to perihelion, flight time, powerplant size, and propulsion on-time. In general, payload gains are affected by increasing any or all of these parameters. Alternatively, when more than adequate payload is available, certain parameters such as power and propulsion time may be selected "sub-optimally" in order to enhance engineering design goals and mission reliability. A strong point is made of reducing propulsion on-time and off-loading the launch vehicle payload below maximum injected mass. This is thought to be the proper design procedure, even in preliminary mission analyses.

Practical accomplishment of the very difficult Halley rendezvous depends upon the development and availability of nuclear-electric propulsion by 1983. A 100 kw NEP system launched by the Titan 3D(7)/Centaur can deliver more than adequate payload in a flight time of only 2.6 years. Propulsion time is held to 15,000 hours for the nominal 500 kg payload. Use of the proposed Shuttle/Centaur/NEP would allow even further reduction in propulsion time.

PROPULSION SYSTEM TECHNOLOGY ASSUMPTIONS

The facing page lists the propulsion system parameters assumed in the present study. In the case of ballistic missions,* a single-stage retro propulsion system employing space-storable propellants and having a multiple restart capability is utilized for all ΔV maneuvers after earth departure through the final rendezvous impulse. The size of the retro stage lies in the range 1000-1700 kg. The midcourse and approach guidance ΔV allowance is 100 m/sec. A separate Earth-storable propulsion system is utilized for comet stationkeeping maneuvers. The solar electric** propulsion parameters are representative of current technology assuming rollout solar arrays and 2-3 kw thruster modules (Friedlander 1970). Specific mass includes the solar array and its associated structure, the thruster and power conditioning modules, and the thrust vector control elements. The overall propulsion efficiency includes a power conditioning efficiency of 91%. The nuclear electric** propulsion specific mass is representative of a thermionic conversion system design. Propulsion system mass is estimated to be 3000 kg at a nominal power design point of 100 kw (Schaupp and Sawyer 1971).

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* Ballistic trajectory requirements are calculated using the multiple-impulse program MULIMP (Waters 1971)

** Low-thrust trajectory requirements are calculated using the CHEBYTOP program (Hahn 1969).

TABLE 5-1

PROPULSION SYSTEM TECHNOLOGY ASSUMPTIONS

- **BALLISTIC FLIGHT MODE**

  SPACE-STORABLE SYSTEM FOR ALL MIDCOURSE, RENDEZVOUS, AND GUIDANCE ΔV REQUIREMENTS.
  $I_{sp} = 400$ SEC, INERT FRACTION $\approx 25\%$

- **SOLAR ELECTRIC FLIGHT MODE**

SPECIFIC MASS	$\alpha_{ps} = 30$ KG/KW
EFFICIENCY	$\eta_{ps} = 62\%$ at $I_{sp} = 3000$ SEC
TANKAGE FRACTION	$k_t = 3\%$
POWER CURVE	$P/P_0 = \dfrac{2.825}{R^2} - \dfrac{1.825}{R^{2.5}}$, $R > 0.652$
	$= 1.329$, $R \leq 0.652$
AUXILIARY POWER	$\Delta P_{AUX} = 0$

- **NUCLEAR ELECTRIC FLIGHT MODE**

SPECIFIC MASS	$\alpha_{ps} = 30$ KG/KW at $P_e = 100$ KW
EFFICIENCY	$\eta_{ps} = 83\%$ at $I_{sp} = 6000$ SEC
TANKAGE FRACTION	$k_t = 3\%$

LAUNCH VEHICLE PERFORMANCE CURVES

Curves of maximum injected mass versus hyperbolic launch velocity are shown for several launch vehicle candidates. Although this study has focused on the Titan/Centaur vehicles, the Shuttle/Centaur performance is shown for comparison purposes. The V_{HL} region of interest for the nuclear electric Halley mission is 1.5 to 3.5 km/sec. For both ballistic and solar electric missions to comets Encke, d'Arrest and Kopff, V_{HL} lies in the range 7.5 to 9.5 km/sec. It is understood that a particular mission design may not necessarily utilize the maximum launch vehicle performance at a given value of V_{HL}. Off-loading can occur when the electric propulsion power rating is significantly less than optimum (maximum net mass), or when other engineering advantages such as a reduction in propulsion on-time is desired. For obvious reasons of "margin of safety" it is best to design the mission below the maximum launch vehicle performance.

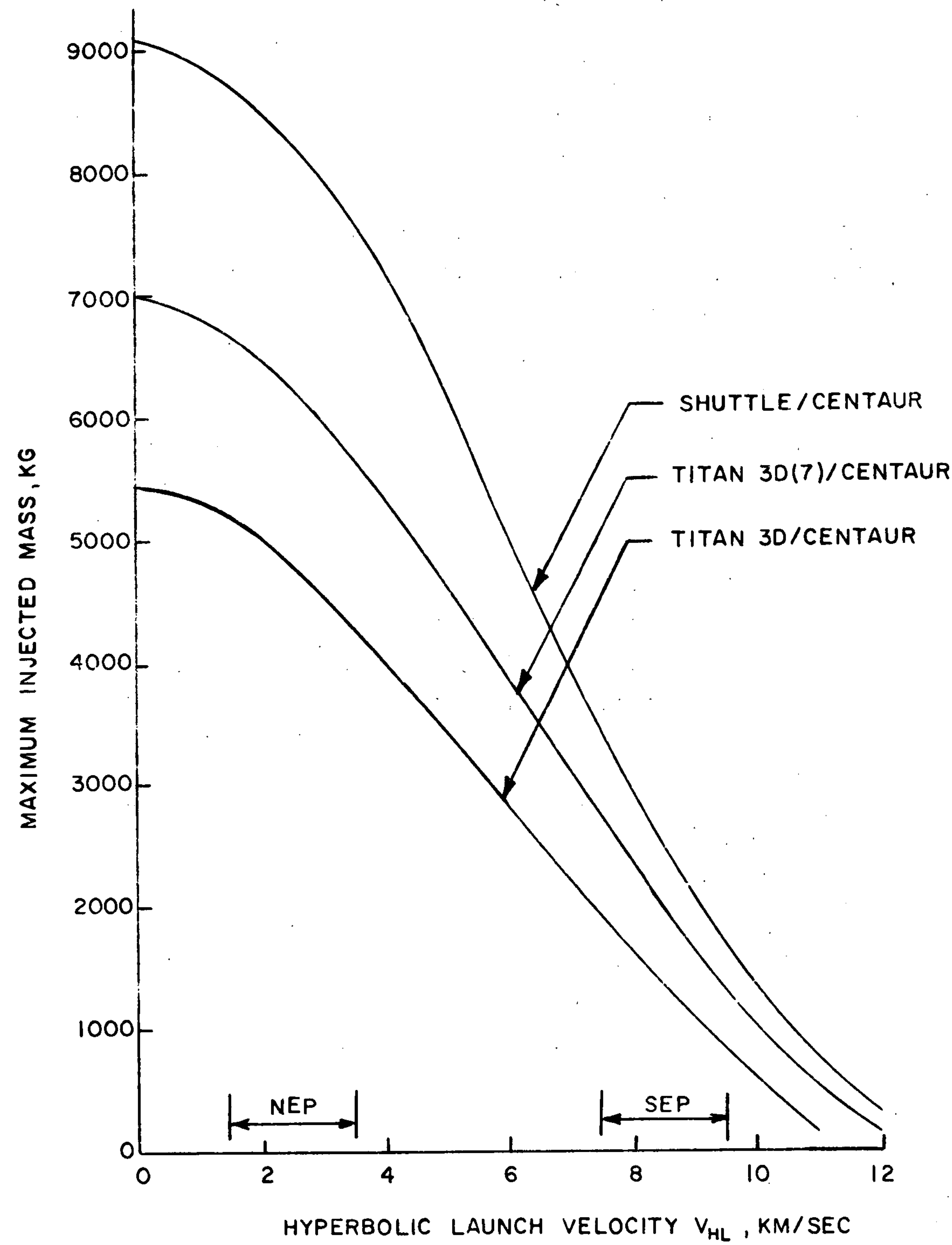

FIGURE 5-1. LAUNCH VEHICLE PERFORMANCE CURVES
1971 ESTIMATING FACTORS HANDBOOK (NASA)

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SOLAR ELECTRIC TRAJECTORY REQUIREMENTS FOR RENDEZVOUS WITH P/ENCKE (1980)

The facing figure shows the effect of arrival time and flight time for missions to P/Encke (1980) apparition). Trajectory energy requirements are described in terms of the parameter J defined as the time integral of thrust acceleration squared. Low values of J imply a smaller propellant expenditure. Assuming current SEP technology (α = 30 kg/kw), the mission J requirement should be less than 10 m^2/sec^3 if reasonable size payloads are to be delivered.

The figure illustrates three trajectory characteristics which are generally true for all comet missions when the arrival date is constrained to a rather narrow region near perihelion.

(1) There exists several flight time "classes" (e.g., 800^d - 1010^d) having different locally optimum flight times for the same arrival date. The J requirement is generally lower for the longer flights.

(2) Within each flight time class, the J requirement decreases as the arrival date approaches perihelion. The incremental change in flight time corresponds closely to the change in arrival date. This simply reflects the fact that the optimum earth launch position is essentially fixed by the comet's orbital geometry.

(3) The sensitivity of J to arrival date increases sharply for the shorter flight time class.

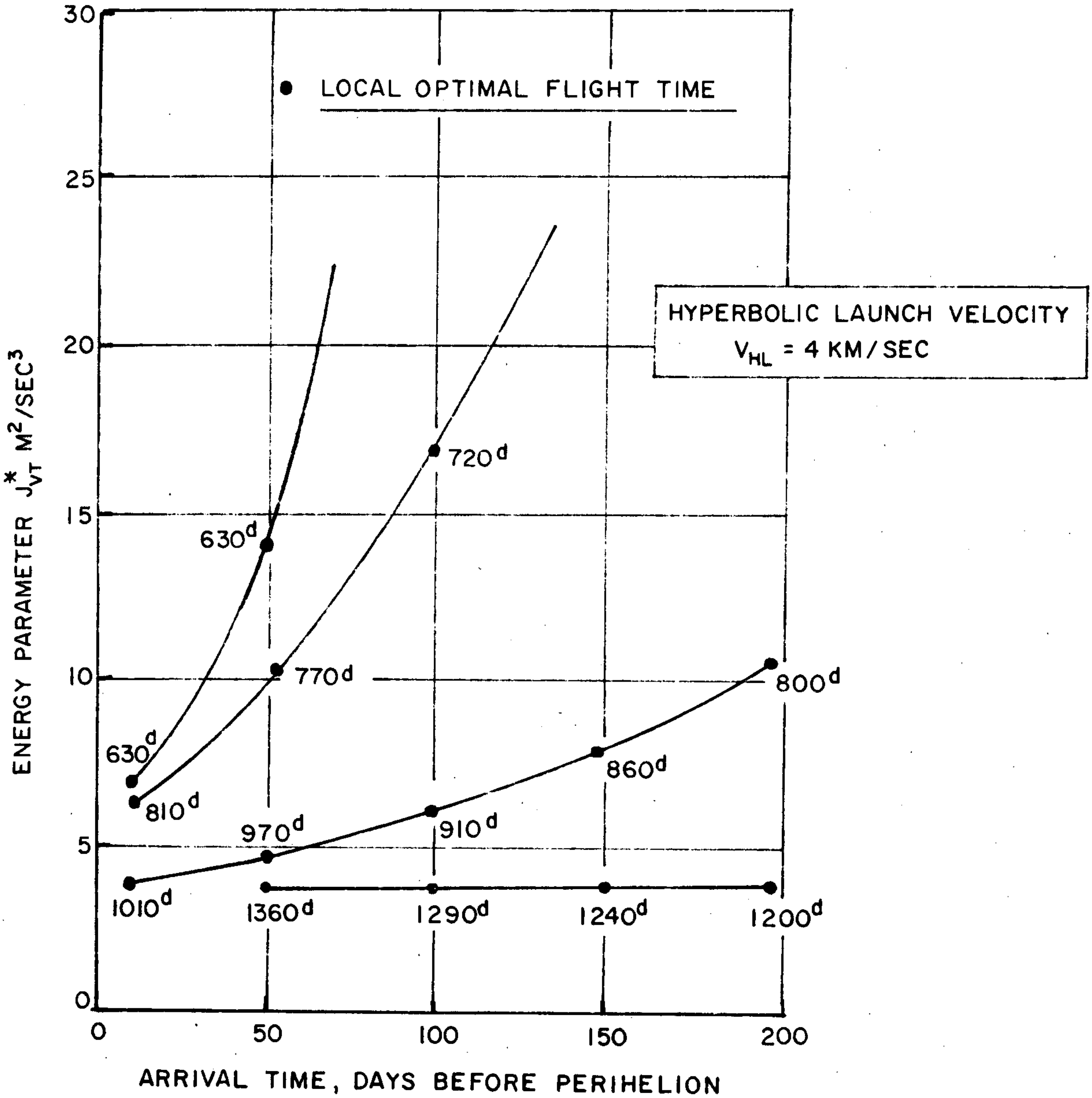

FIGURE 5-2. SOLAR ELECTRIC TRAJECTORY REQUIREMENTS FOR RENDEZVOUS WITH P/ENCKE(1980).

SOLAR ELECTRIC PAYLOAD CAPABILITY FOR RENDEZVOUS WITH P/ENCKE (1980).

The payload implication of the previous figure is shown for segments of two flight time classes. Net spacecraft mass capability of the Titan 3D/Centaur launch vehicle is given for constrained (lower than optimum) SEP power designs of 10, 15 and 20 kw. The payload requirement for rendezvous missions has been determined to be about 500 kg. Although this requirement could be satisfied by the 630 day trajectory, the arrival date must be closer to perihelion than is desired. Coma activity for P/Encke begins about 80 days before perihelion. Hence, from a science standpoint, rendezvous should occur no later than 50 days before perihelion. Imposing this constraint would eliminate the 630 day mission from further consideration. The 960 day mission launched in 1978 and arriving 50 days before perihelion has considerable excess payload capability even at a power rating of 10 kw.

A large payload performance margin implies design choices which are available to enhance mission success and/or minimize cost, e.g., (1) low risk technology subsystems, (2) redundancy, (3) reduce propulsion on-time, (4) constrain thrust pointing angles, (5) extend launch window.

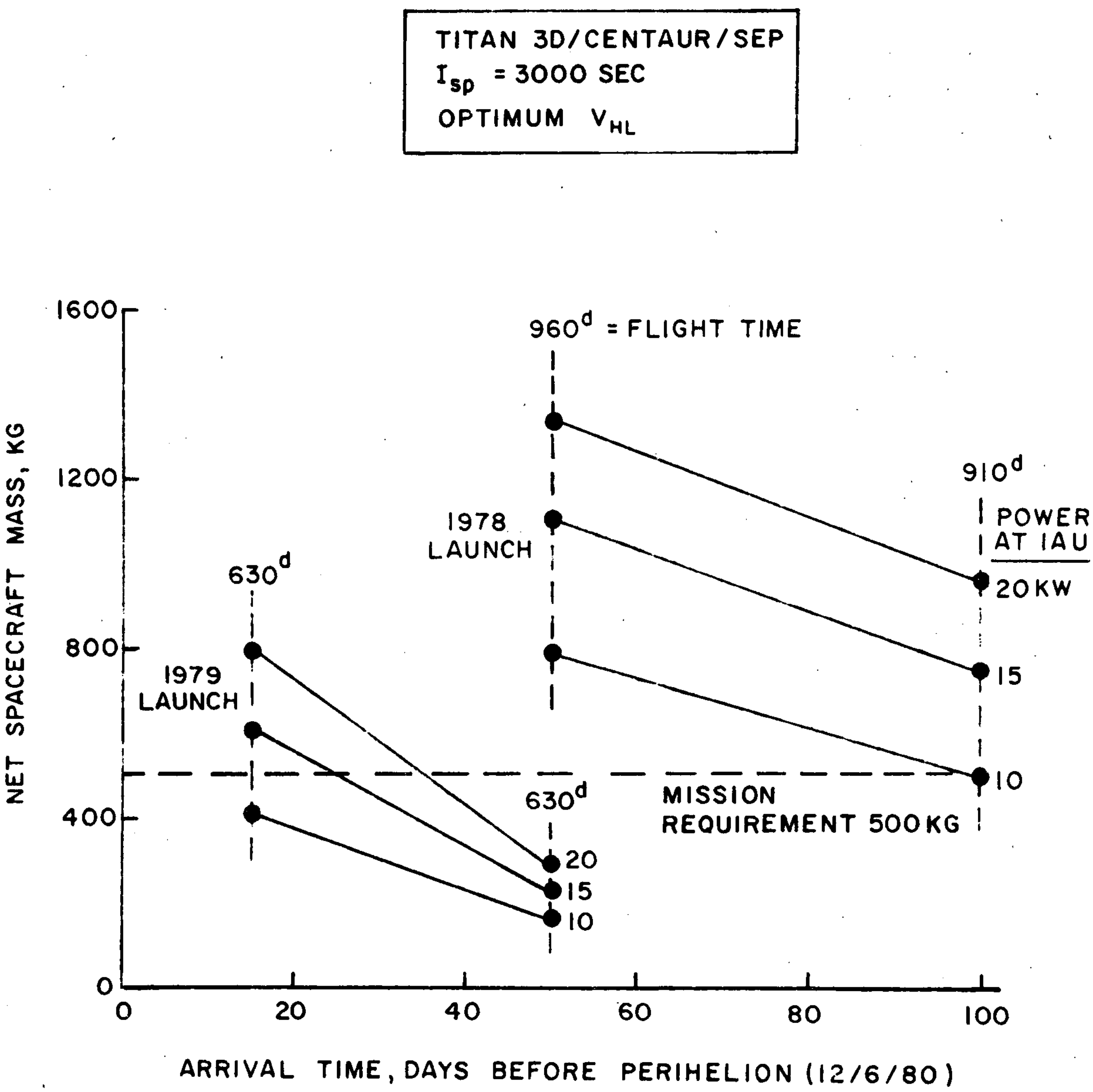

FIGURE 5-3. SOLAR ELECTRIC PAYLOAD CAPABILITY FOR RENDEZVOUS WITH P/ENCKE (1980)

COMPARISON OF SEP PAYLOAD CAPABILITY FOR 1980 AND 1984 RENDEZVOUS OPPORTUNITIES WITH P/ENCKE

Curves of maximum net spacecraft mass are shown as a function of solar power input for two flight time classes of 1.5-2 years and 2.5-3 years. The arrival date in each case is 50 days before Encke's perihelion (12/6/80 or 3/27/84). The increased net mass capability of the 1984 apparition is a result of a more favorable orbital (position) geometry relationship between Earth and P/Encke. The net mass difference between the two mission opportunities is particularly significant in the case of the shorter flight time trajectories. For example, the 630 day mission launched in January 1979 cannot achieve the 500 kg requirement even at an optimum power design of 50 kw. In contrast, the 700 day mission launched in March 1982 can deliver 500 kg with an 18 kw SEP system; alternatively, a 10 day delay in arrival time (T_p - 40^d) reduces the SEP power requirement to 13 kw.

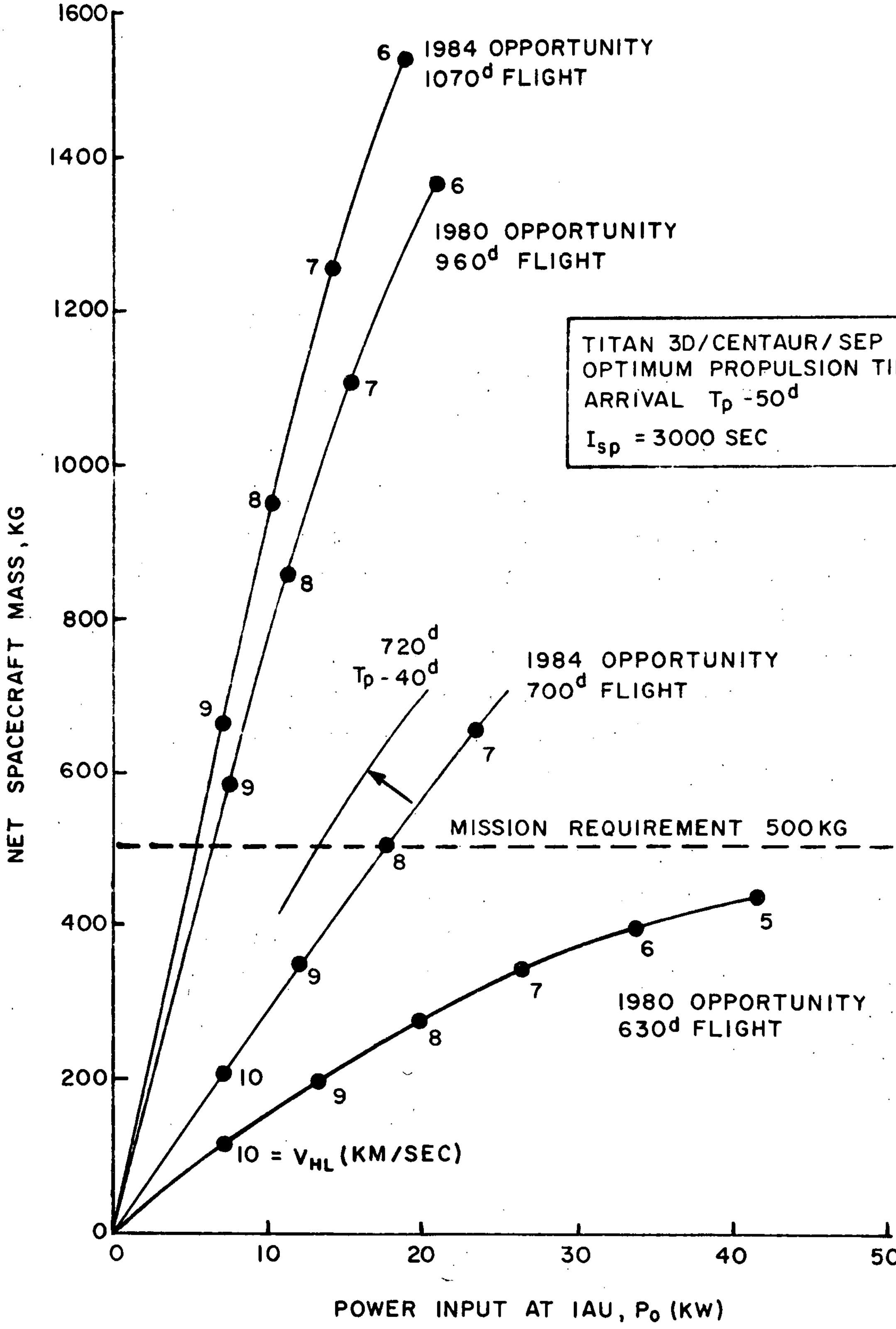

FIGURE 5-4. COMPARISON OF SEP PAYLOAD CAPABILITY FOR 1980 AND 1984 RENDEZVOUS OPPORTUNITIES WITH P/ENCKE.

SOLAR ELECTRIC PAYLOAD CAPABILITY FOR RENDEZVOUS WITH P/d'ARREST (1982)

Net spacecraft mass capability of the Titan 3D/Centaur launch vehicle is shown as a function of arrival time for constrained SEP power designs of 10, 15 and 20 kw. The 3-year class mission launched in 1979 provides a net mass far higher than the nominal requirement of 500 kg. The 2-year class mission launched in 1980 will give adequate net mass for a 15 kw SEP powerplant if rendezvous occurs no sooner than 45 days before perihelion. Such a rendezvous date constraint is compatible with the science objectives for P/d'Arrest (see discussion in Section 2). An example of a nominal mission selection is the 740-day flight arriving 25 days before perihelion and yielding a maximum net mass of 680 kg for a 15 kw powerplant. Propulsion time for this example is equal to the 740-day flight time (i.e., no coast periods). However, the 180 kg payload margin may be used to reduce propulsion time thereby gaining increased mission reliability.

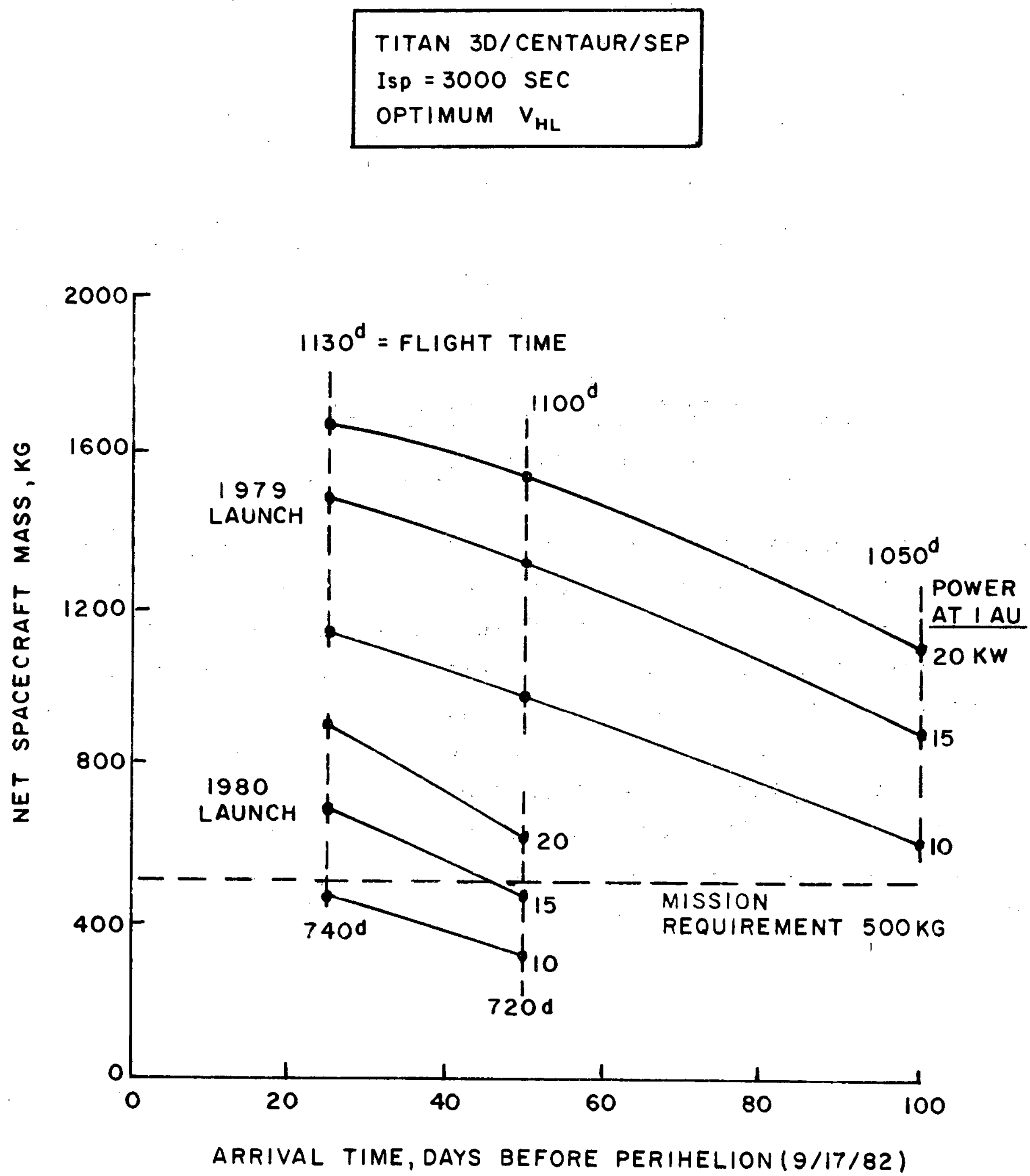

FIGURE 5-5. SOLAR ELECTRIC PAYLOAD CAPABILITY FOR RENDEZVOUS WITH P/d'ARREST (1982)

SOLAR ELECTRIC PAYLOAD CAPABILITY FOR RENDEZVOUS WITH P/KOPFF (1983)

Net spacecraft mass capability of the Titan 3D/Centaur launch vehicle is shown as a function of arrival time for constrained SEP power designs of 10, 15 and 20 kw. The 3-year class mission launched in 1980 provides significantly more net mass than the nominal 500 kg requirement. The 2-year class mission launched in 1981 will give adequate net mass for a 15 kw SEP powerplant if rendezvous occurs no sooner than 37 days before perihelion. As an in the case of P/d'Arrest, such a rendezvous date constraint is compatible with the science objectives for P/Kopff.

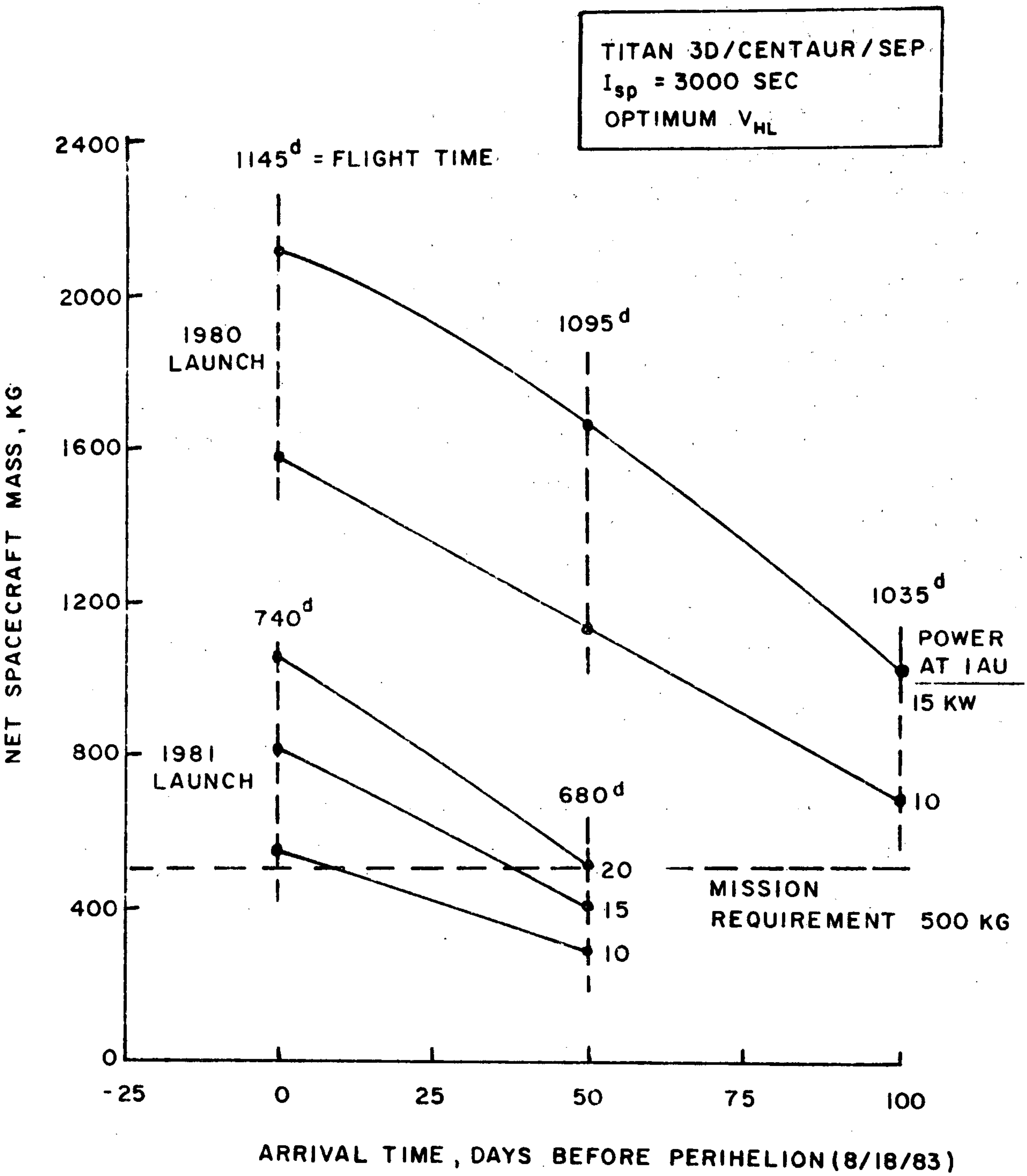

FIGURE 5-6. SOLAR ELECTRIC PAYLOAD CAPABILITY FOR RENDEZVOUS WITH P/KOPFF (1983)

PROPULSION TIME TRADEOFF FOR SOLAR ELECTRIC MISSIONS

Employing the Titan 3D/Centaur launch vehicle, the SEP system parameters are fixed at typical design values of 15 kw power, 3000 sec. specific impulse, and 8 km/sec. launch velocity. The facing figure shows the effect of propulsion on-time on net mass capability for missions to Encke, d'Arrest and Kopff. The maximum propulsion boundary corresponds to the maximum injected mass of the Titan 3D/Centaur (1640 kg at V_{HL} = 8 km/sec.). Since the net mass at these points lies above the mission requirement of 500 kg, propulsion time may be decreased significantly by reducing the launch vehicle injected mass and thereby increasing the thrust acceleration. For Encke, the net mass requirement* is met at a propulsion on-time of about 560 days and an injected (initial) mass of 1200 kg. The d'Arrest and Kopff missions have propulsion on-time (and injected mass) requirements of 570 days (1430 kg) and 484 days (1300 kg), respectively.

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* A propellant penalty of about 20 kg is included to account for an extended launch window. This is discussed further in Section 7.

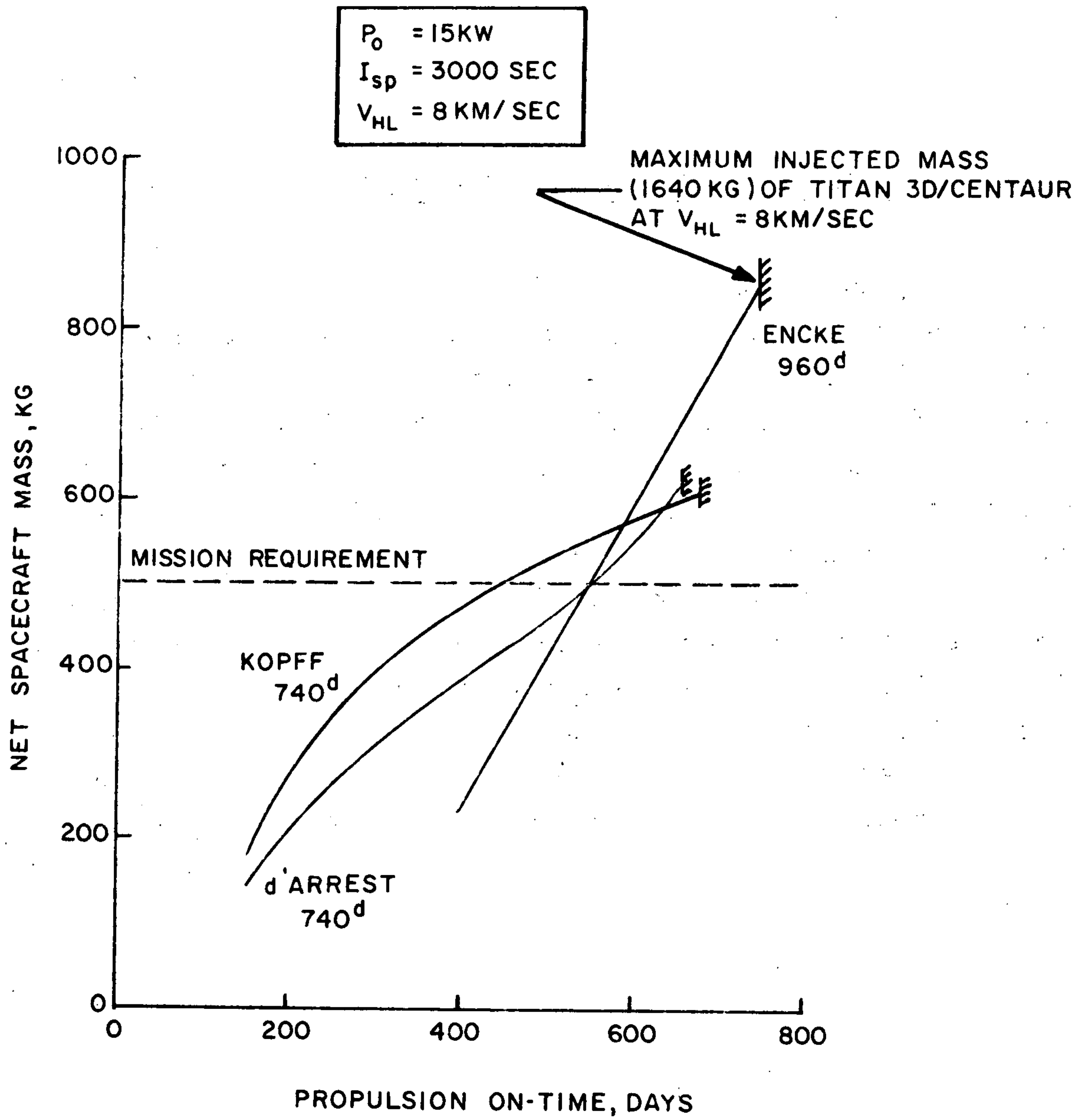

FIGURE 5-7. PROPULSION TIME TRADEOFFS FOR SOLAR ELECTRIC MISSIONS

BALLISTIC MISSION PAYLOAD CAPABILITY

The payload capability of 3-impulse ballistic trajectories to comets Encke, d'Arrest and Kopff is shown in Figure 5-8. Unlike SEP characteristics, the ballistic payload tends to decrease rapidly as the rendezvous point approaches perihelion. The optimum rendezvous point is about 100 days before perihelion for P/Encke and P/Kopff, and is about 30 days before perihelion for P/d'Arrest. The reader should note that the particular flight time class and launch vehicle selected for each mission example is such that the maximum payload (net mass) is approximately 500 kg. The 4-year ballistic mission to P/Kopff can employ the Titan 3D/Centaur, but the 3.5-year mission to P/Encke and the 5-year mission to P/d'Arrest require the 7-segment version of the Titan vehicle.

COMET/APPARITION	FLIGHT TIME	LAUNCH VEHICLE
ENCKE/80	~ 3.5 YR.	TITAN 3D(7)/CENTAUR
d'ARREST/82	~ 5.0 YR.	TITAN 3D(7)/ CENTAUR
KOPFF/83	~ 4.0 YR.	TITAN 3D/-CENTAUR

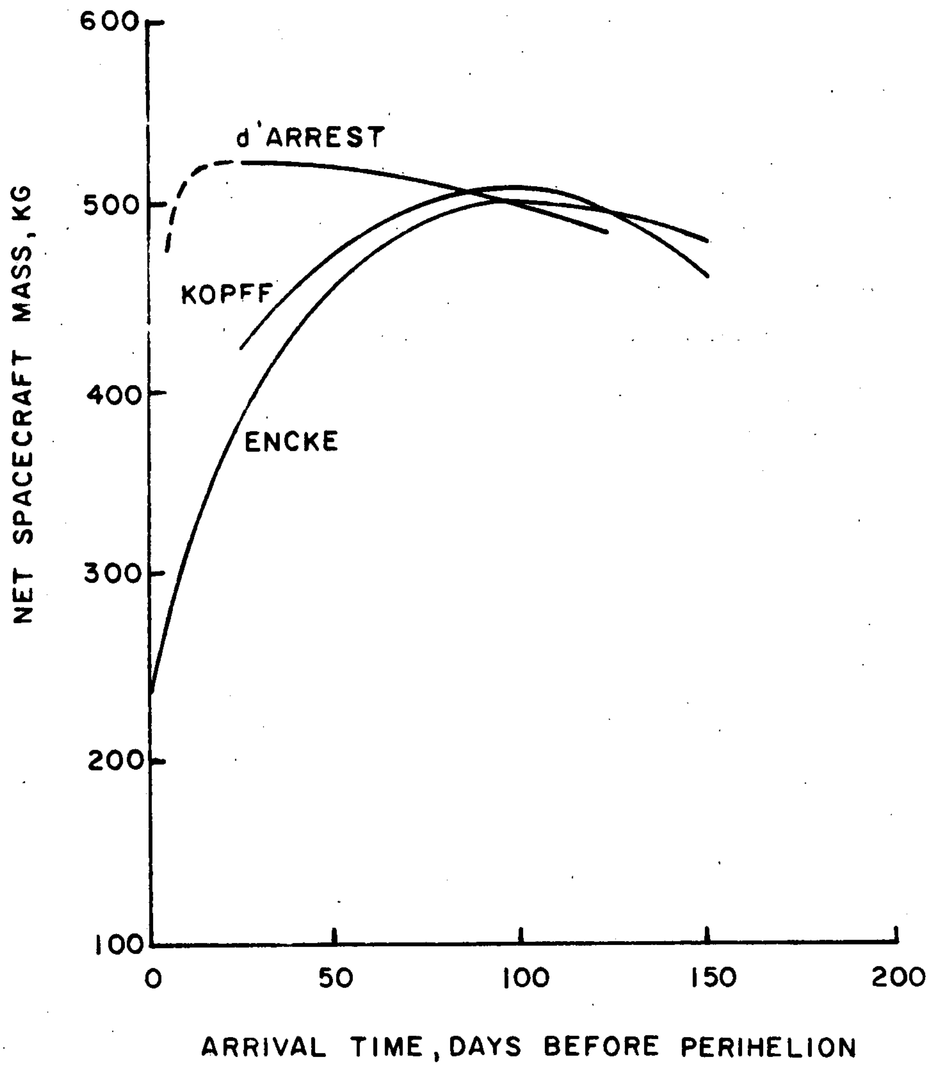

FIGURE 5-8. BALLISTIC MISSION PAYLOAD CAPABILITY

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PERFORMANCE TRADEOFFS FOR NUCLEAR ELECTRIC HALLEY RENDEZVOUS MISSION (950 DAYS)

The illustration shows the performance trade-offs for a 100 kw NEP system launched to hyperbolic escape by the Titan 3D(7)/Centaur. The flight time to Halley is 950 days with rendezvous occurring 50 days before perihelion. In the grid of net mass versus propulsion on-time, the solid curve shows the effect of varying design specific impulse for maximum injected mass (6500 kg at V_{HL} = 2 km/sec.). The all-propulsion flight delivers a maximum net spacecraft mass of 930 kg utilizing a specific impulse of about 7500 seconds. At 500 kg net mass, the propulsion on-time reduces to 570 days and the specific impulse to about 5400 seconds. The broken-line curve illustrates the preferred design procedure of off-loading the launch vehicle. Hence, at an I_{sp} of 6000 sec. the mission requirement is satisfied for a slightly longer propulsion on-time (615 days). Note that the injected mass is reduced to 6100 kg, which gives a 400 kg "margin of safety" on launch vehicle performance.

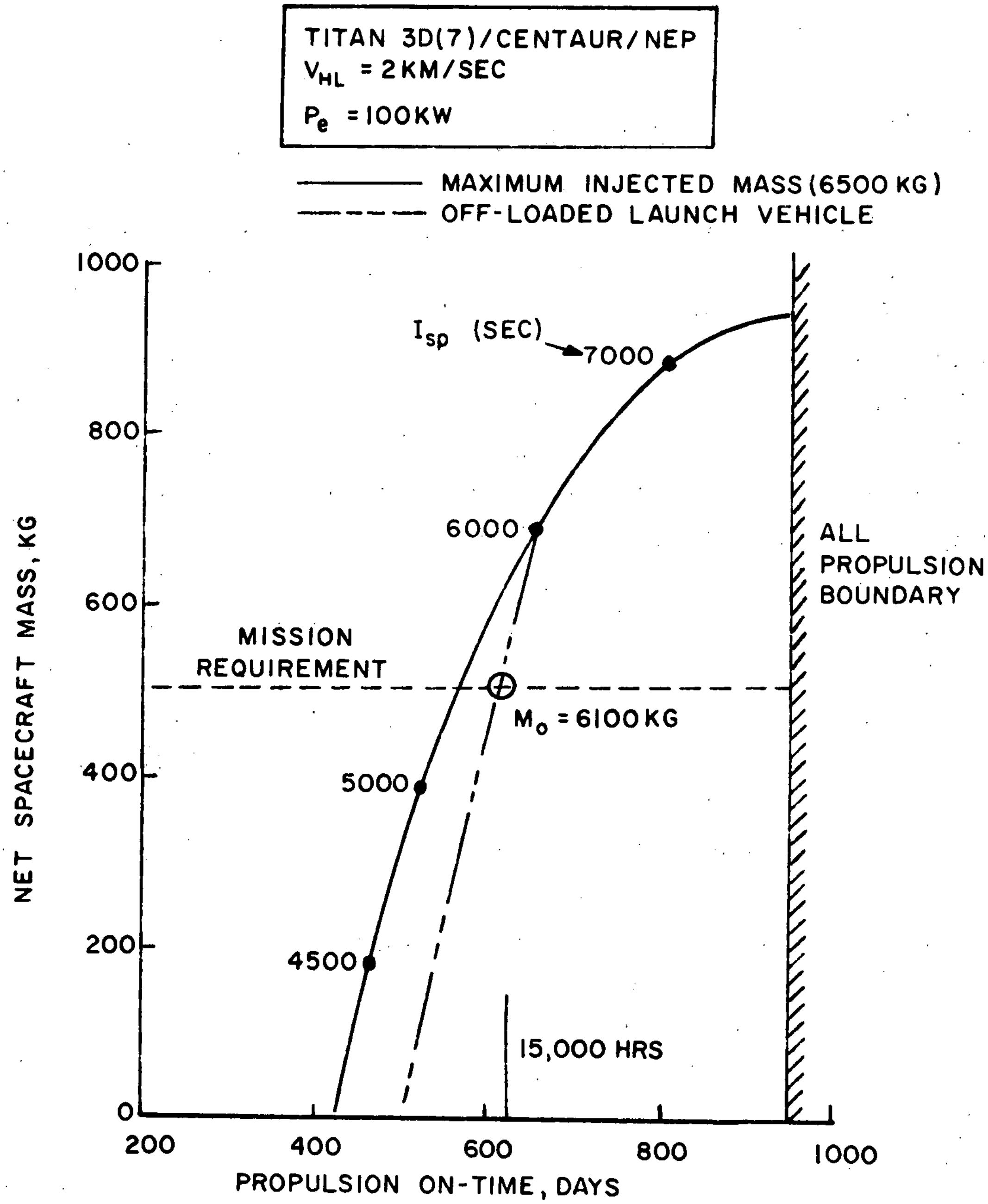


FIGURE 5-9. PERFORMANCE TRADEOFFS FOR NUCLEAR ELECTRIC HALLEY RENDEZVOUS MISSION (950 DAYS)

BASELINE MISSION SELECTIONS

Characteristics of representative mission examples and delivery modes are shown in the table below. The Titan/Centaur (5 or 7 segment solids) is the baseline launch vehicle in all cases. Net spacecraft mass delivered to rendezvous is nominally 500 kg (1100 lbs). For missions to Encke, d'Arrest and Kopff the tradeoff is between solar electric propulsion and ballistic flight modes. SEP is preferred for these missions because the flight time is substantially shorter, and the payload "margin of safety" is ultimately greater. The nominal SEP payloads shown are not the maximum capability even for the constrained power of 15 kw. Rather, these selections were made with the aim of reducing thrust-on time. Nuclear electric propulsion is the preferred mode for the Halley mission because of the rather short flight time and, again, the payload margin of safety. It is uncertain whether NEP will be developed and made operational for the 1983 launch. One alternative is the Jupiter-assisted SEP mission which can provide adequate payload. However, this alternative is not very attractive because of the 8 year flight time requirement.

TABLE 5-2

BASELINE MISSION SELECTIONS

COMET/YEAR	MISSION MODE	LAUNCH DATE	FLIGHT TIME (YRS)	ARRIVAL DAYS BEFORE T_P	THRUST TIME (HRS)	LAUNCH VEHICLE	RENDEZVOUS PAYLOAD (KG)	
							NOMINAL	MAXIMUM
ENCKE/80	SEP	3/ 2/78	2.63	50	13,500	T3D/CENT	500	1100
	BALLISTIC	2/23/77	3.51	100	-	T3D(7)/CENT	500	500
d'ARREST/82	SEP	8/13/80	2.03	25	13,700	T3D/CENT	500	690
	BALLISTIC	8/14/77	4.96	50	-	T3D(7)/CENT	500	520
KOPFF/83	SEP	7/14/81	2.03	25	11,600	T3D/CENT	500	630
	BALLISTIC	7/17/79	3.95	50	-	T3D/CENT	500	500
HALLEY/86	NEP	5/16/83	2.60	50	14,800	T3D(7)/CENT	500	930
	SEP/GA	8/25/77	8.32	50	27,000	T3D(7)/CENT	500	500

SEP P_0 = 15 KW, I_{SP} = 3000 SEC

NEP P_E = 100 KW, I_{SP} = 6000 SEC

BALLISTIC SPACE-STORABLE RETRO I_{SP} = 400 SEC

GA JUPITER GRAVITY-ASSIST

LAUNCH CONDITIONS
BASELINE MISSION SELECTIONS

Baseline launch velocity (V_{HL}) is between 8 and 9.4 km/sec with the exception of the NEP mission to Halley's Comet. In this case 2 km/sec is near-optimum because the trajectory energy requirements can be supplied more efficiently by the NEP system rather than by the launch vehicle. The high V_{HL} for the SEP mission applications is a result of selecting a lower than optimum powerplant size of 15 kw. Declination of the launch asymptote (DLA) satisfies Eastern Test Range safety requirements with the exception of the Encke mission. The ballistic Encke mission requirement is borderline. In the SEP case, the 45° declination can be achieved by adding 84 m/sec to the characteristic launch velocity. The injected mass penalty is about 80 kg. This is quite acceptable since the launch vehicle off-loading is 440 kg for the Encke mission baseline design.

TABLE 5-3

LAUNCH CONDITIONS

BASELINE MISSION SELECTIONS

COMET/YEAR	MISSION MODE	V_{HL} KM/SEC	DLA (EQUATORIAL REF)
ENCKE/80	SEP	8.0	-44°.8
	BALLISTIC	8.2	-36°.6
d'ARREST/82	SEP	8.0	-29°.6
	BALLISTIC	9.2	- 3°.8
KOPFF/83	SEP	8.0	6°.8
	BALLISTIC	8.0	- 1°.3
HALLEY/86	NEP	2.0	1°.8
	SEP/GA	9.4	23°.5

BASELINE MISSION TRAJECTORIES TO P/ENCKE

Ballistic (3-impulse) and solar electric trajectories to Comet Encke are compared. The basic trajectory orientation is dictated by the comet's orbital geometry, namely, the line of apsides. Thus, the earth launch position is essentially the same for both the ballistic and SEP flight modes. Note also that the ballistic midcourse impulse point lies close to the line of apsides, i.e., nearly 180° from the launch position. The sum of the midcourse and rendezvous impulses in the ballistic case is 3.89 km/sec. The baseline SEP trajectory has two coast periods; an initial coast of 266 days and a 133 day coast beginning 784 days after launch.

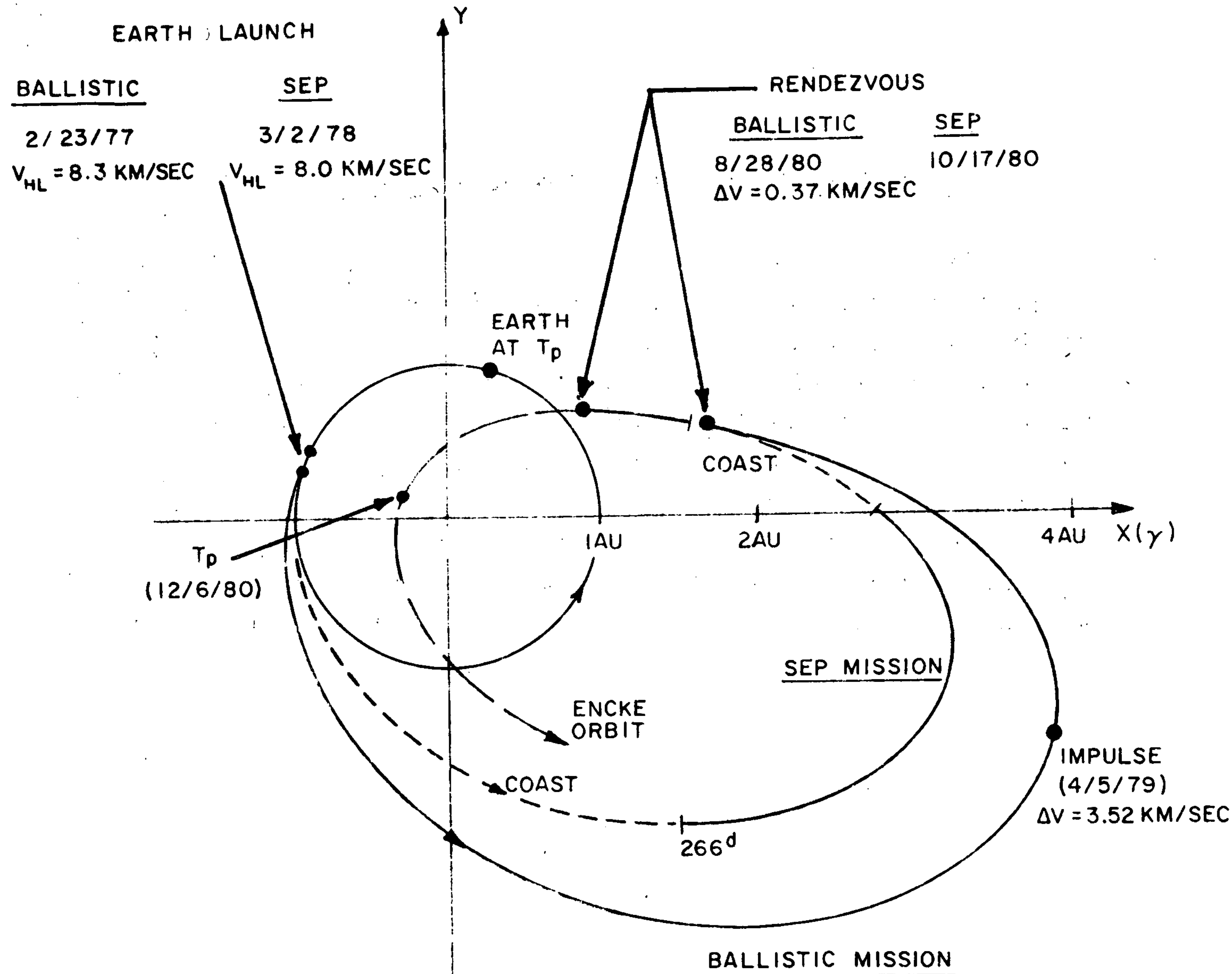


FIGURE 5-10. BASELINE MISSION TRAJECTORIES TO P/ENCKE

BASELINE MISSION TRAJECTORIES TO P/d'ARREST

The much larger spatial extent of the ballistic trajectory reflects the 3 year longer flight time compared to the SEP mission. Launched nearly in the ecliptic plane, the midcourse impulse of 2.37 km/sec rotates the trajectory plane to coincide closely with d'Arrest's orbit of 19.6° inclination. In contrast, the SEP trejectory launched at a slightly lower value of hyperbolic velocity (V_{HL}) has an initial inclination of 12°. Because of the large V_{HL} thrust initiation does not occur until 148 days after launch. A shorter coast period of 22 days begins 488 days after launch.

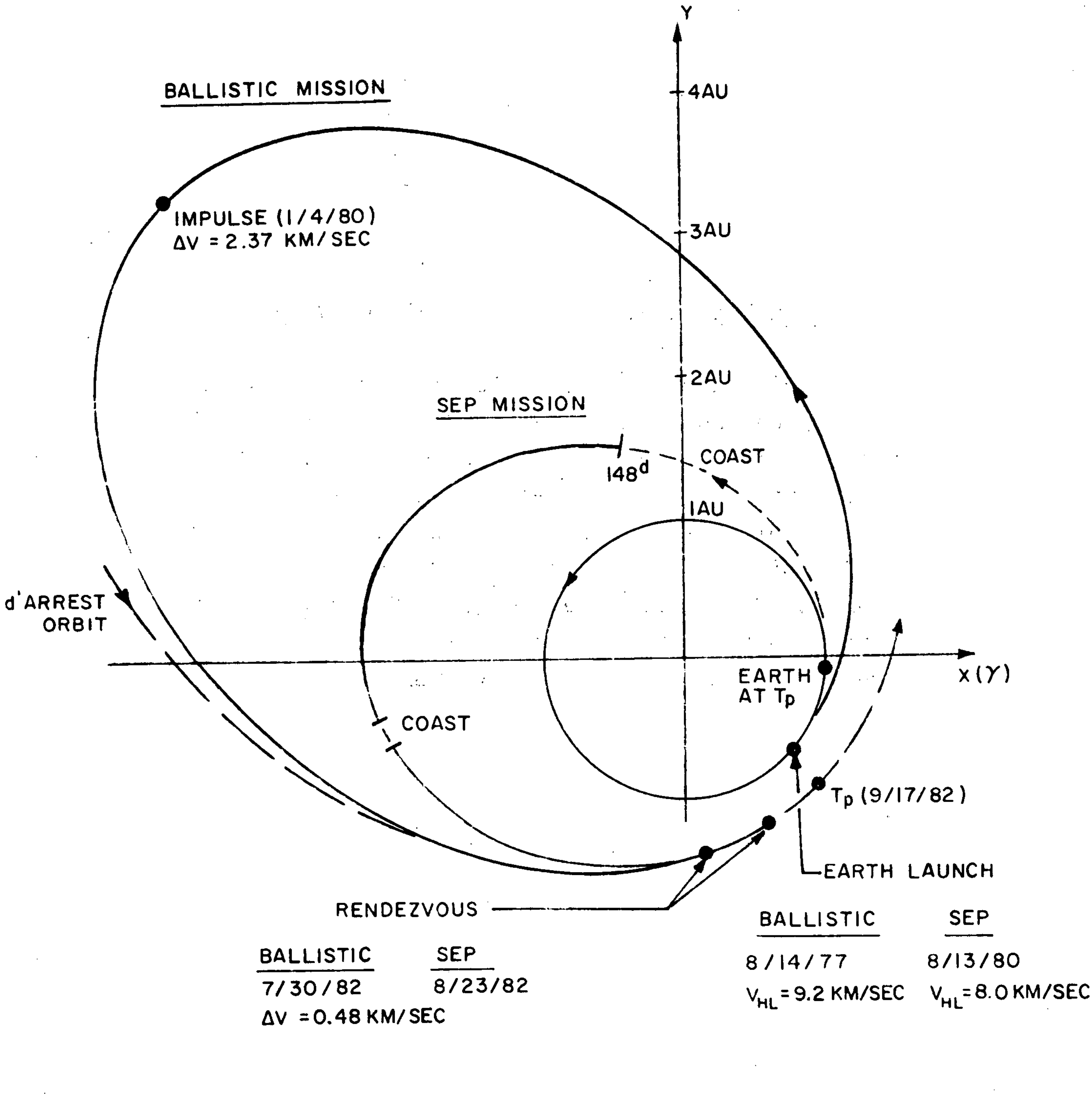


FIGURE 5-11. BASELINE MISSION TRAJECTORIES TO P/d'ARREST

BASELINE MISSION TRAJECTORIES TO P/KOPFF

This baseline ballistic mission launched in 1979 employs an optimum sequence of 3 impulses after Earth departure. The sum of the midcourse and rendezvous ΔV's is 3.07 km/sec. Rendezvous occurs 50 days before the perihelion date (T_p) of Kopff. The SEP mission is launched in 1981 and rendezvous occurs 25 days before perihelion. The rather long initial coast period of 256 days is a result of the large value of launch velocity (V_{HL}).

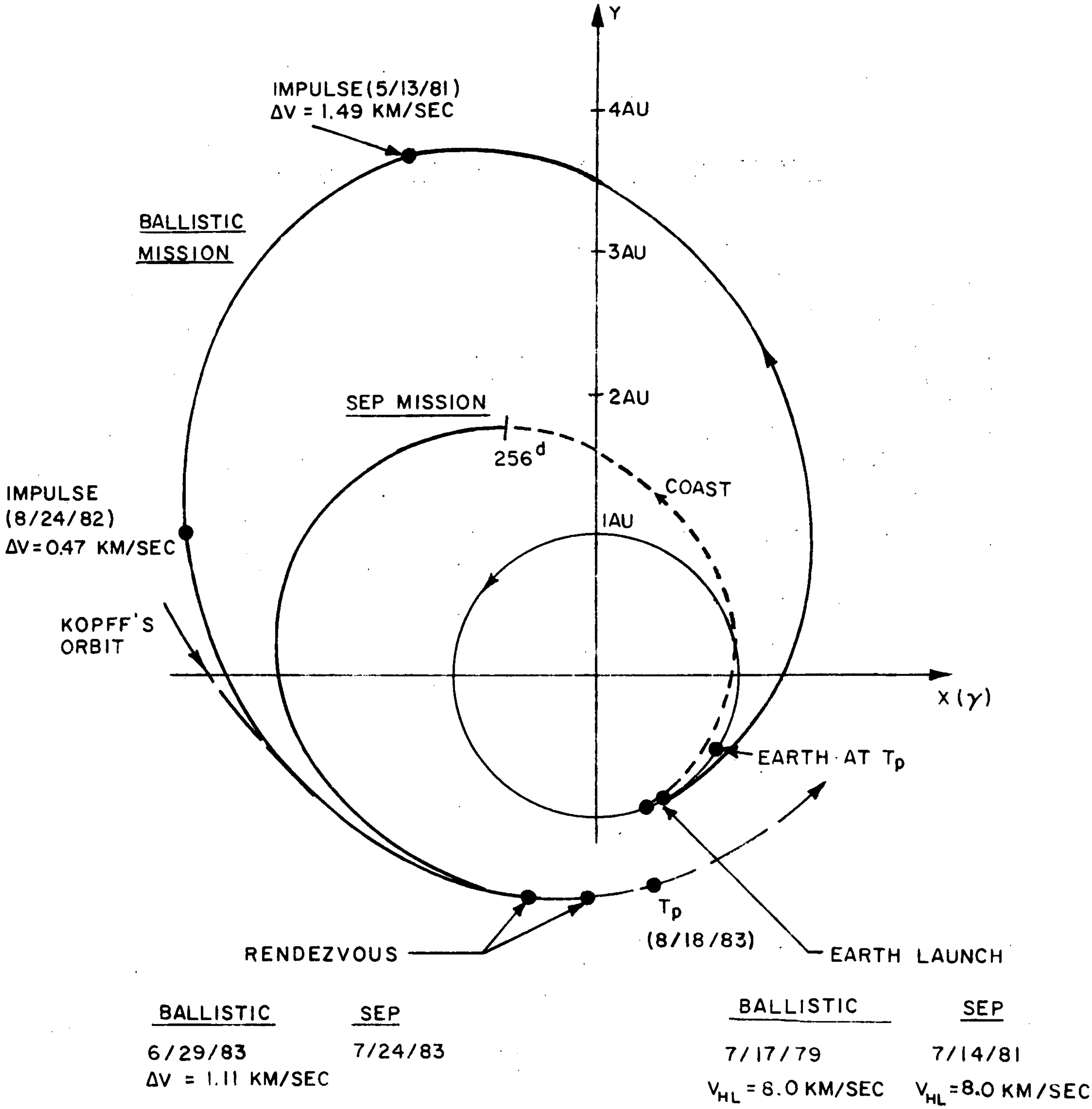


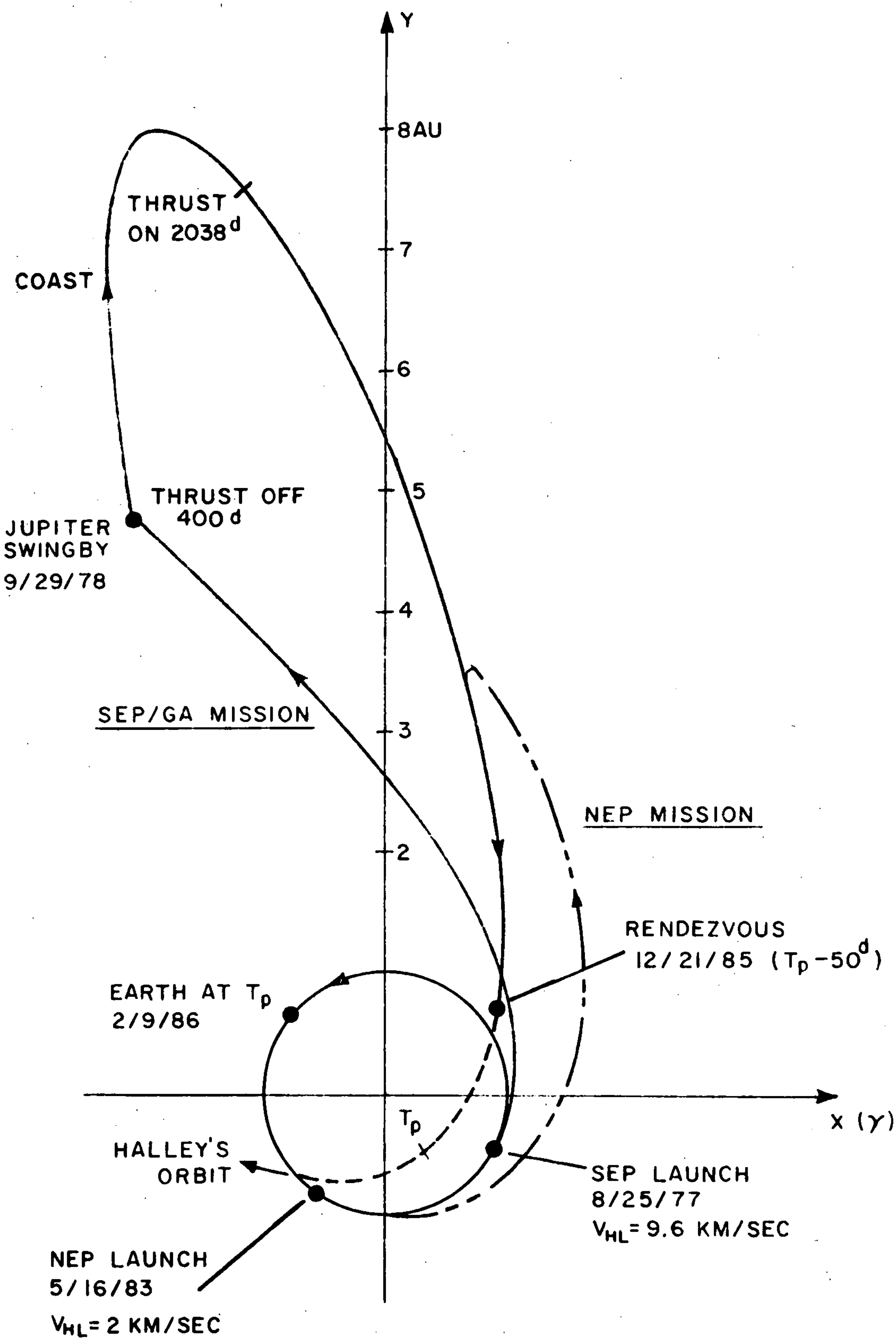
FIGURE 5-12. BASELINE MISSION TRAJECTORIES TO P/KOPFF

BASELINE MISSION TRAJECTORIES TO P/HALLEY

A comparison of the nuclear electric and solar electric (Jupiter-assisted) trajectories to Halley's Comet is shown. Rendezvous in each case occurs 50 days before perihelion. The 2.6 year NEP mission is launched in May 1983. A 331 day coast period begins 128 days after launch. The change from posigrade to retrograde motion takes place near the aphelion point (3.6 AU) where the trajectory turns tightly into Halley's orbit. The 8.3 year SEP mission is launched in August 1977. Hyperbolic velocity and pericenter distance at Jupiter swingby are 19 km/sec and 7.22 Jupiter radii, respectively. The SEP trajectory is retrograde after Jupiter departure, and thrust is not reinitiated for 1638 days. Total thrust-on time is 1326 days; 324 days on the Earth-Jupiter leg and 1002 days on the Jupiter-Halley leg.

FIGURE 5-13

BASELINE MISSION TRAJECTORIES TO P/HALLEY



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SECTION 6: GUIDANCE AND STATIONKEEPING OPERATIONS

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SECTION 6 SUMMARY

Focusing on the Encke mission, this section describes the problem areas of midcourse and approach guidance, and stationkeeping (translation) maneuvers after rendezvous. Implementation of the guidance function entails the use of several tracking sensor systems to obtain orbit determination information, and propulsion maneuvers for flight path correction. The sensor systems include: (1) Earth-based radio (DSN) tracking of the spacecraft, (2) Earth-based telescopic tracking of the comet, and (3) on-board tracking of the comet during the approach and rendezvous phase. The most likely candidate for the on-board tracker is a vidicon system which transmits pictures of the comet against the stellar background. A scanning photometer has been suggested by others as a simpler and less expensive alternative to TV, but this device is inherently less accurate and its application to cometary targets is uncertain at this time.

Velocity errors at Earth departure and thrust execution errors enroute will cause very large (1-2 x 10^6 km) terminal deviations if left uncorrected. However, the effect of these errors can be measured by the DSN, and trajectory corrections can be made at moderate propellant cost - even in the case of ballistic flights. The major error source at rendezvous is the comet's ephemeris uncertainty. Even after comet recovery by Earth-based telescopes the comet's position may be uncertain by many thousands of kilometers. Reduction of this error to the order of 10-100 km can be accomplished only by on-board tracking and trajectory corrections during the approach phase (about 50 days before rendezvous).

The ballistic mission to P/Encke requires a total guidance ΔV of about 100 m/sec using 3-4 impulsive maneuvers. In the case of the SEP mission, it is shown that coast periods during the heliocentric transfer are important in that they allow the DSN to recover high accuracy tracking of spacecraft position and velocity. The propellant chargeable to all SEP guidance maneuvers is less than 10 kg. Recovery of P/Encke by the on-board tracker occurs about 60 days before rendezvous at a distance of 4×10^6 km. The cross-range (miss distance) position uncertainty relative to the comet is decreased from 3000 km to 400 km at recovery, and thereafter decreases below 10 km several days before rendezvous. The range uncertainty, on the other hand, cannot be estimated accurately until 10 days before rendezvous; at 10 days the uncertainty is 1300 km and at 4 days it is 100 km. Range estimation is enhanced if the nominal miss distance has a non-zero value (~ 1000 km aim-point offset is adequate).

A representative stationkeeping/translation maneuver sequence is proposed for each of the comet missions. This sequence covers a time interval of 60 to 100 days after rendezvous and a spatial region of $\pm$ 20,000 km about the sun line. Total ΔV for these maneuvers varied between 167 m/sec (P/Encke) and 69 m/sec (P/Halley). The Encke maneuvers can be performed with the SEP system for a propellant expenditure of about 6 kg and a 4 percent thrust duty cycle (2.4 days/60 days).

APPROACH GUIDANCE FUNCTIONAL DIAGRAM

The schematic diagram shows the separation of Earth-based and on-board functions related to tracking, computation and control. The comet-stellar reference information applies only to the approach phase of the mission. Direct comet tracking is necessary to reduce comet ephemeris uncertainty to the 10 - 100 km level. Earth-based recovery of the comet will generally occur first. This results in an immediate improvement of the comet's position-in-orbit error to 10,000 - 20,000 km, and can be useful for early approach-phase guidance prior to on-board recovery. The on-board comet tracker will likely consist of a vidicon system which views the comet against the stellar background. An alternative concept would relate the comet's direction to the sun/canopus attitude reference system, but this is inherently less accurate. Although the diagram shows that all computation functions are performed at Earth-based facilities, it may be necessary to transfer some functions to the spacecraft during the final rendezvous and stationkeeping maneuvers (because of communications time delay).

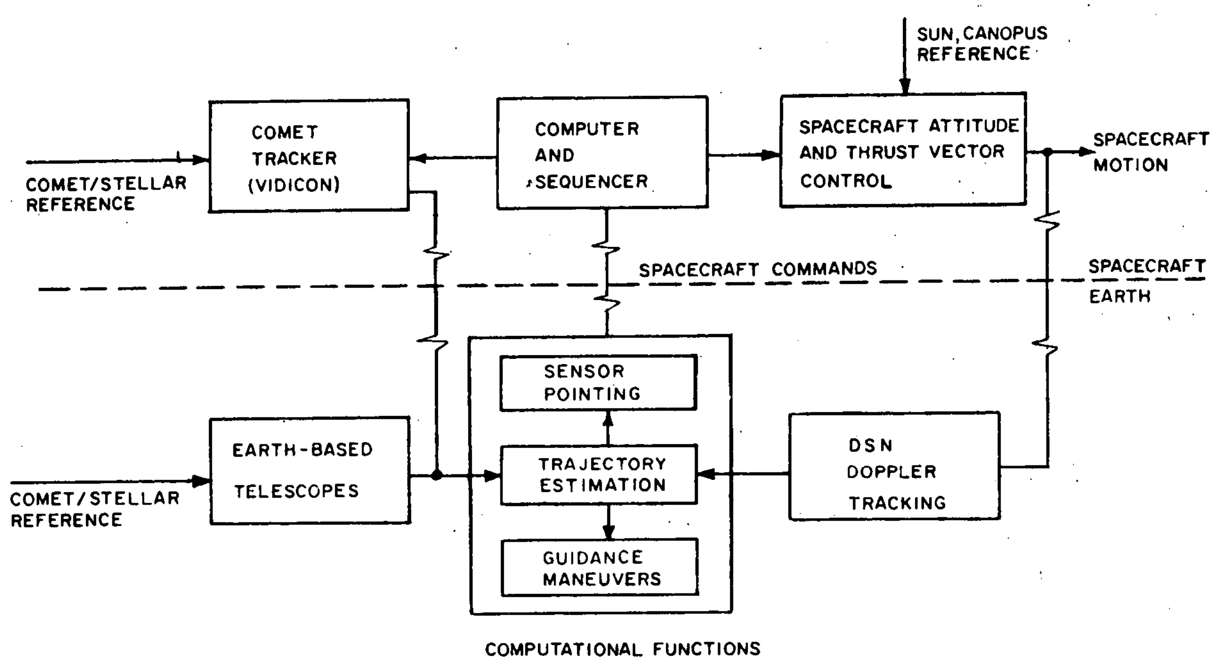

FIGURE 6-1. APPROACH GUIDANCE FUNCTIONAL DIAGRAM

GUIDANCE ANALYSIS - BALLISTIC MISSION TO P/ENCKE

Error sensitivity is shown for the two trajectory subarcs connecting the Earth launch, midcourse impulse and rendezvous terminals. The midcourse position error would be 0.8×10^6 km assuming a 3 m/sec injection error left uncorrected. A post-injection maneuver of 5 m/sec (1σ) takes out most of the midcourse position error. Assuming a 0.5% execution error applied to the 3.52 km/sec midcourse impulse results in a miss distance and range error at rendezvous of 1.5×10^6 km and 0.5×10^6 km, respectively. A 30 m/sec post-midcourse guidance maneuver reduces these errors to 30,000 km and 15,000 km, respectively (note that the comet ephemeris is now the major source of error). The approach maneuver of 14 m/sec is made several days after comet acquisition by the on-board tracker. The remaining range error of 2200 km is corrected at no ΔV cost by adjusting the time to initiate the rendezvous retro maneuver; this time variation is about 1.5 hours (1σ). A small post-rendezvous maneuver is needed to transfer the spacecraft to the immediate vicinity of the nucleus. The total guidance ΔV requirement is just under 100 m/sec.

TABLE 6-1

GUIDANCE ANALYSIS

BALLISTIC MISSION TO P/ENCKE

A. OPEN-LOOP ERRORS (1σ)

1. EARTH LAUNCH - MIDCOURSE IMPULSE
(INJECTION ERROR 3M/SEC SPHERICAL DISTRIBUTION)

POSITION ERROR = 0.8×10^6 km

2. MIDCOURSE IMPULSE - RENDEZVOUS
(EXECUTION ERROR 0.5% SPHERICAL DISTRIBUTION)

MISS ERROR = 1.5×10^6 km
RANGE ERROR = 0.5×10^6 km

3. COMET EPHEMERIS

MISS ERROR = 27,000 km
RANGE ERROR = 14,000 km

B. GUIDANCE CORRECTIONS (1σ)

	ΔV	Δ(MISS)	Δ(RANGE)
POST-INJECTION	5 M/SEC	$> 10^6$ km	$> 10^6$ km
POST-MIDCOURSE	30	30,000	15,000
APPROACH	14	160	2,200
RENDEZVOUS	-	160	100
POST-RENDEZVOUS	2	10	10

TOTAL(MEAN + 3σ) = 92 M/SEC

SEP TRAJECTORY ERRORS - BASELINE MISSION TO P/ENCKE

The SEP guidance analysis makes use of a computer program developed at JPL by Rourke and Jordan (1971). Typical error source assumptions are taken from the above reference. The upper graph on the facing page shows the open-loop position and velocity deviation from the nominal trajectory assuming an initial velocity error of 3 m/sec and a thrust acceleration vector error of 1%. These one-sigma errors are taken to be spherically distributed among the three coordinate directions. If the spacecraft were left unguided the terminal position and velocity deviations would be 1.7×10^6 km and 205 m/sec, respectively.

The lower graph shows the uncertainty in measuring position and velocity assuming a typical doppler tracking schedule by the Deep Space Network. Previous studies have pointed out the corrupting effect of thrust acceleration noise on tracking accuracy. This effect is apparent in the graph and may be correlated with the coast-thrust propulsion sequence. For example, at the thrust initiation times* of 425 days and 914 days the velocity uncertainty begins to rise sharply (position uncertainty being an integral effect is delayed). However, because high tracking accuracy is recovered during coast periods, the maximum errors are held to under 4000 km and 0.4 m/sec. Terminal position uncertainty is only 750 km. These results underline the importance of designing the nominal trajectory to include one or more coast periods - particularly near the rendezvous point.

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* The trajectory used in the guidance analysis is slightly different from the final baseline selection described in Figure 5-10. This difference is of negligible consequence to the guidance results.

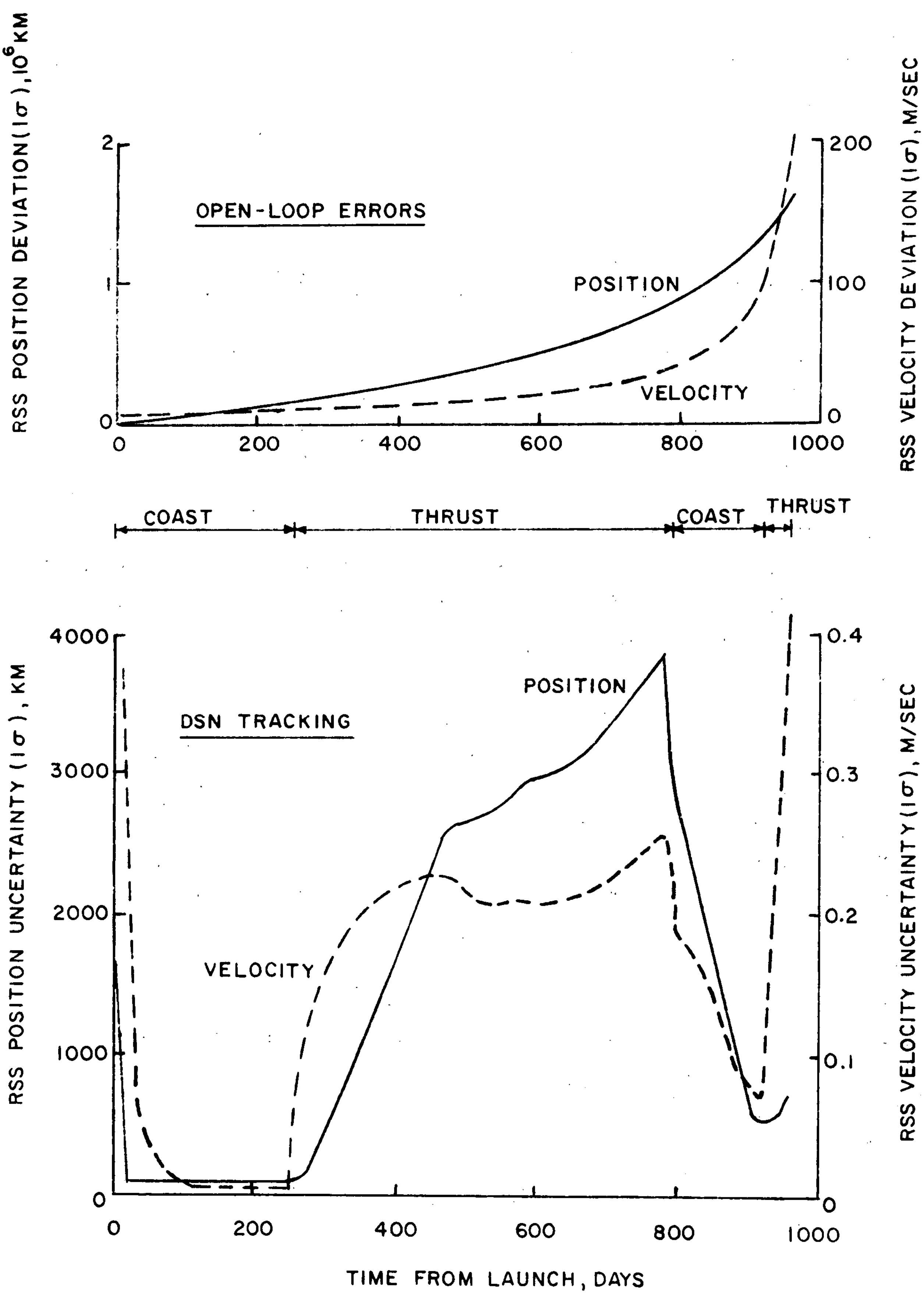
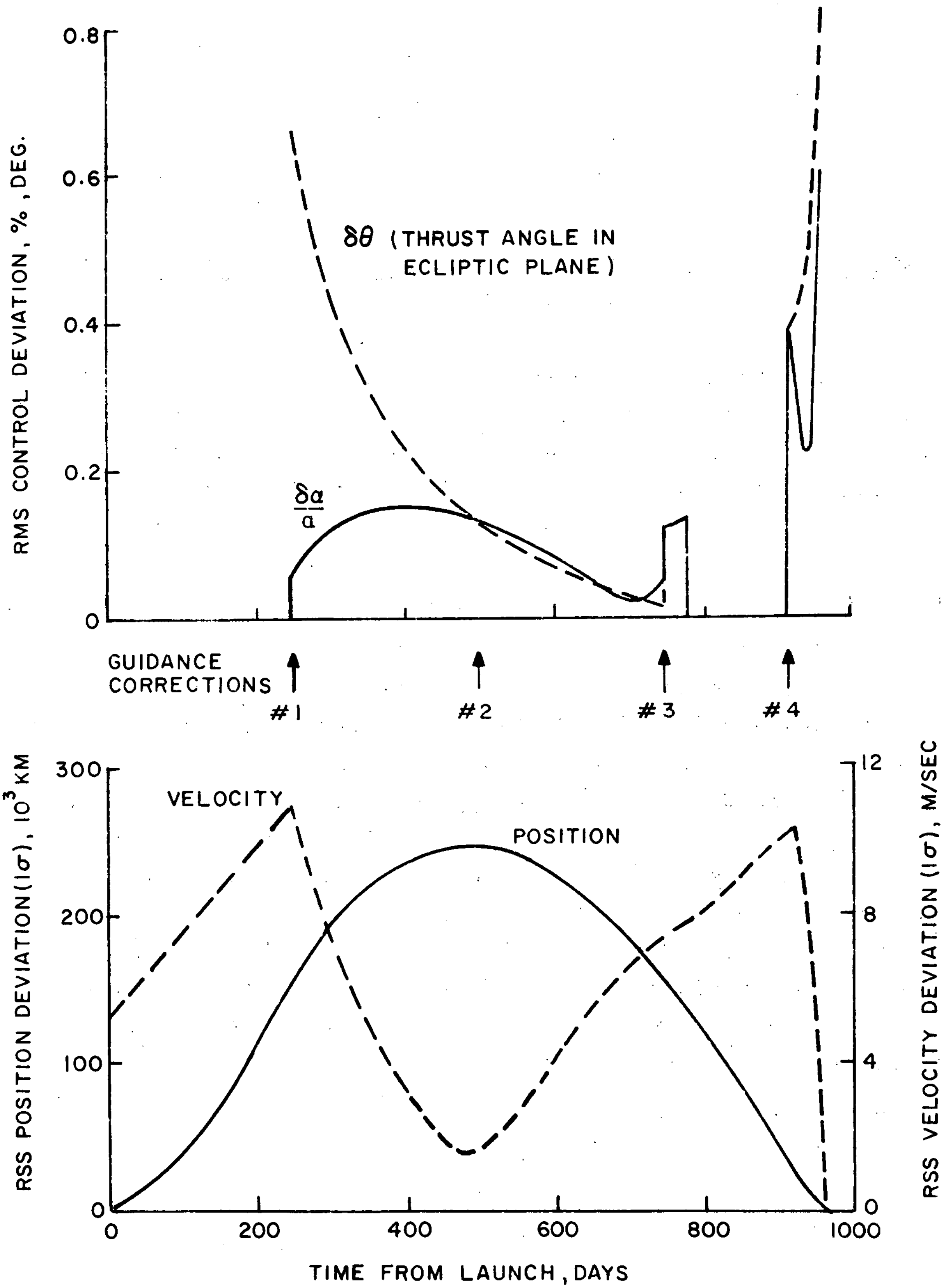


FIGURE 6-2.
SEP TRAJECTORY ERRORS, BASELINE MISSION TO P/ENCKE

SEP MIDCOURSE GUIDANCE - BASELINE MISSION TO P/ENCKE

The upper graph on the facing page shows the RMS time history of the closed-loop guidance program. The example considers four corrections or updates of the thrust program based on current tracking information at the time points 250, 500, 750 and 914 days. It is assumed that both magnitude and direction of acceleration can be controlled, at least to the degree of linearization validity. The maximum control requirement is less than 1% (magnitude) and 1° (direction). These requirements should be easily met with current thruster and attitude control designs.

The lower graph shows the closed-loop trajectory deviation resulting from the guidance program. Maximum position and velocity deviations are 245,000 km and 11 m/sec, respectively. The terminal errors are only slightly higher than the DSN tracking errors, i.e., 1,000 km and 0.5 m/sec. It is important to point out that these terminal errors do not include the comet ephemeris uncertainty. Comet position error is at least an order of magnitude larger, and must be taken out during the final approach phase utilizing on-board tracking information. Approach guidance characteristics are described in subsequent figures.



SEP MIDCOURSE GUIDANCE, BASELINE MISSION TO P/ENCKE
FIGURE 6-3.

EFFECT OF NOMINAL MISS DISTANCE ON APPROACH POSITION ACCURACY SEP MISSION TO P/ENCKE

Spacecraft position relative to the comet is separated into two components; "range" is along the approach velocity direction and "miss distance" is orthogonal to this direction. The facing figure shows the reduction of position uncertainty as a function of time-to-rendezvous assuming that on-board optical sightings are taken at 1 day intervals with an accuracy of 20" (random error). Kalman filter or least-squares processing is also assumed.

Angular information is sensitive to miss distance errors at large spacecraft-comet distances. However, the sensitivity to range errors becomes effective only during the last several days before rendezvous when the spacecraft-comet distance is relatively small. The figure points out the importance of designing the mission to have a non-zero value of nominal miss distance (aim point offset). The nominal miss should not be too large, however, since the spacecraft must be brought to the immediate vicinity of the nucleus (~ 100 km) after rendezvous. A compromise value of 1000 km nominal miss distance appears to be a suitable choice.

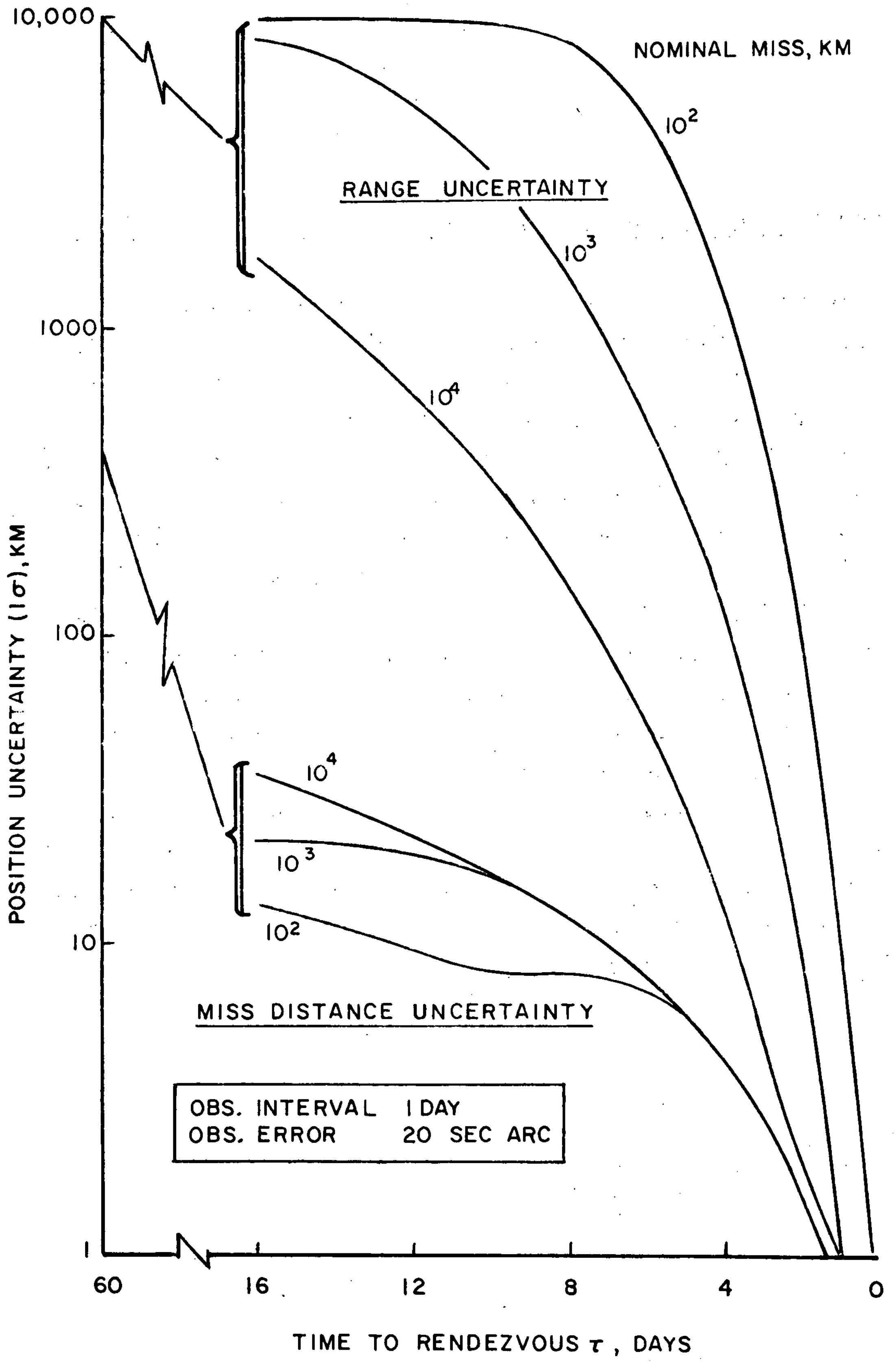


FIGURE 6-4. EFFECT OF NOMINAL MISS DISTANCE ON APPROACH POSITION ACCURACY, SEP MISSION TO P/ENCKE

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APPROACH ORBIT DETERMINATION - SEP MISSION TO P/ENCKE

Earth-based and on-board tracking are compared for the solar electric baseline mission to P/Encke. Errors in the comet's orbital elements (prior to recovery in 1980) are estimated to have the following one-sigma values: $\Delta a = 2 \times 10^{-4}$ AU, $\Delta e = 10^{-5}$, $\Delta T_p = 0.01^d$, $\Delta i = 2''$, $\Delta\Omega = 2''$, $\Delta\omega = 10''$. The resulting initial uncertainties in range and miss distance are 29,000 km and 18,000 km, respectively. Earth-based recovery occurs about 100 days before rendezvous (150 days before perihelion), and effects an immediate improvement in position uncertainty. Continued Earth-based tracking further improves range information but has little effect on miss distance. Assuming that the vidicon detectability threshold is 9th magnitude, on-board recovery occurs about 60 days before rendezvous. Miss distance uncertainty drops immediately to 400 km. After 50 days of continued tracking the miss uncertainty is only 10 km. In contrast, range information does not improve significantly until 10 days before rendezvous. Range uncertainty is 100 km at 4 days to rendezvous.

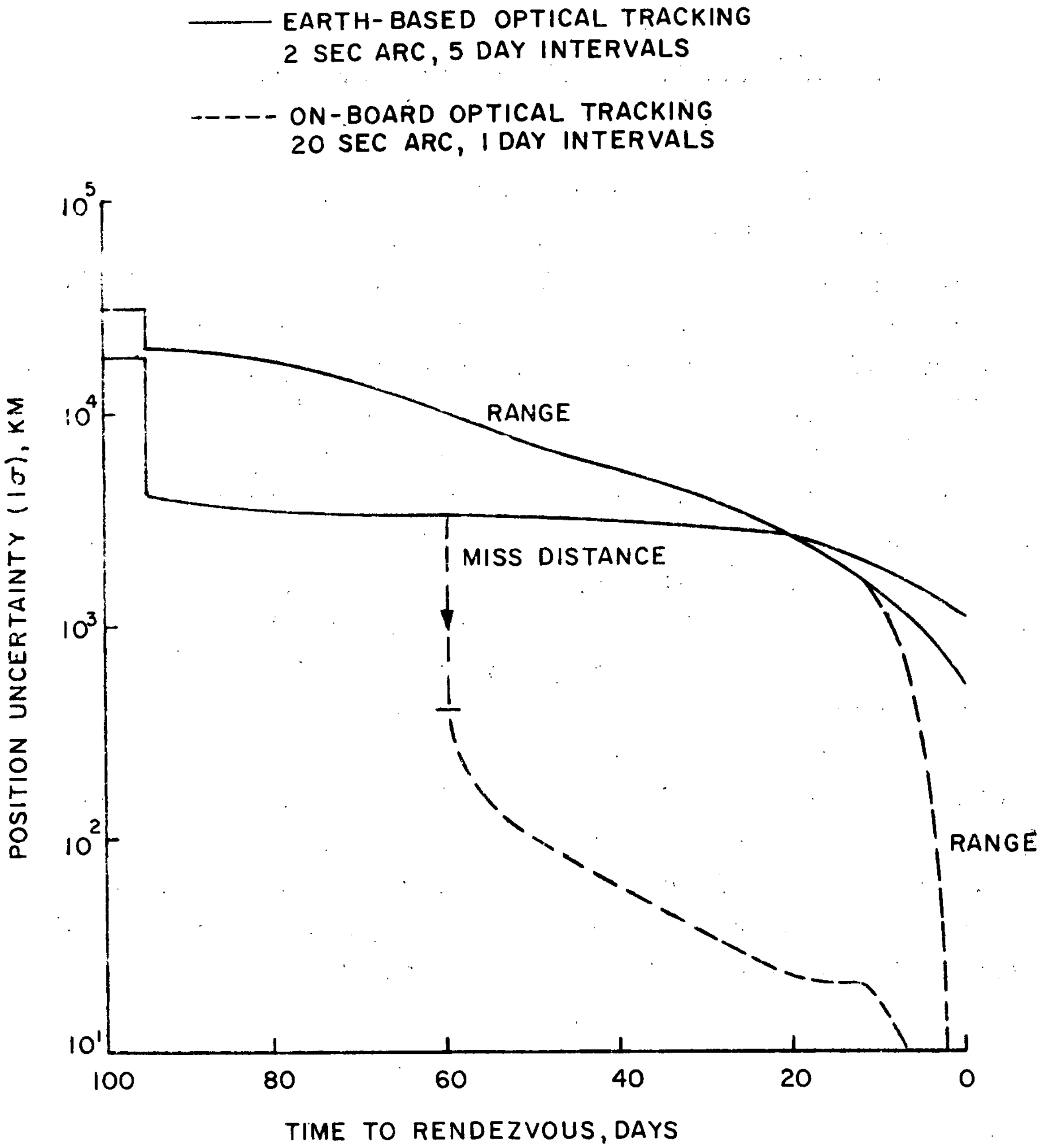


FIGURE 6-5. APPROACH ORBIT DETERMINATION, SEP MISSION TO P/ENCKE

ILLUSTRATION OF TWO-CORRECTION GUIDANCE POLICY FOR SEP APPROACH TO P/ENCKE

A two-correction approach guidance policy is illustrated for the control of range and miss distance errors. The example assumes that thrust acceleration magnitude is controllable (to first-order) as well as thrust direction. The initial estimates of range and miss distance deviations are 29,000 km and 18,000 km, respectively. The actual range deviation is assumed to be 36,000 km (estimate plus 1σ estimation error). Guidance is initiated 50 days before rendezvous, the policy being to null the estimated errors at the nominal rendezvous time. Maximum values of acceleration and angle control are about 5% and 2°, respectively. With reference to the previous figure, the range estimation error at 8 days before rendezvous has been reduced to 900 km. A second correction policy is initiated at this time. If the rendezvous time is allowed to change by one-half day, the acceleration control is held to within 9%. Propellant expenditure attributed to the guidance maneuvers is only 5 kg. It may be necessary to limit the acceleration control to one or two percent; this could be effected by allowing a larger change in the rendezvous time.

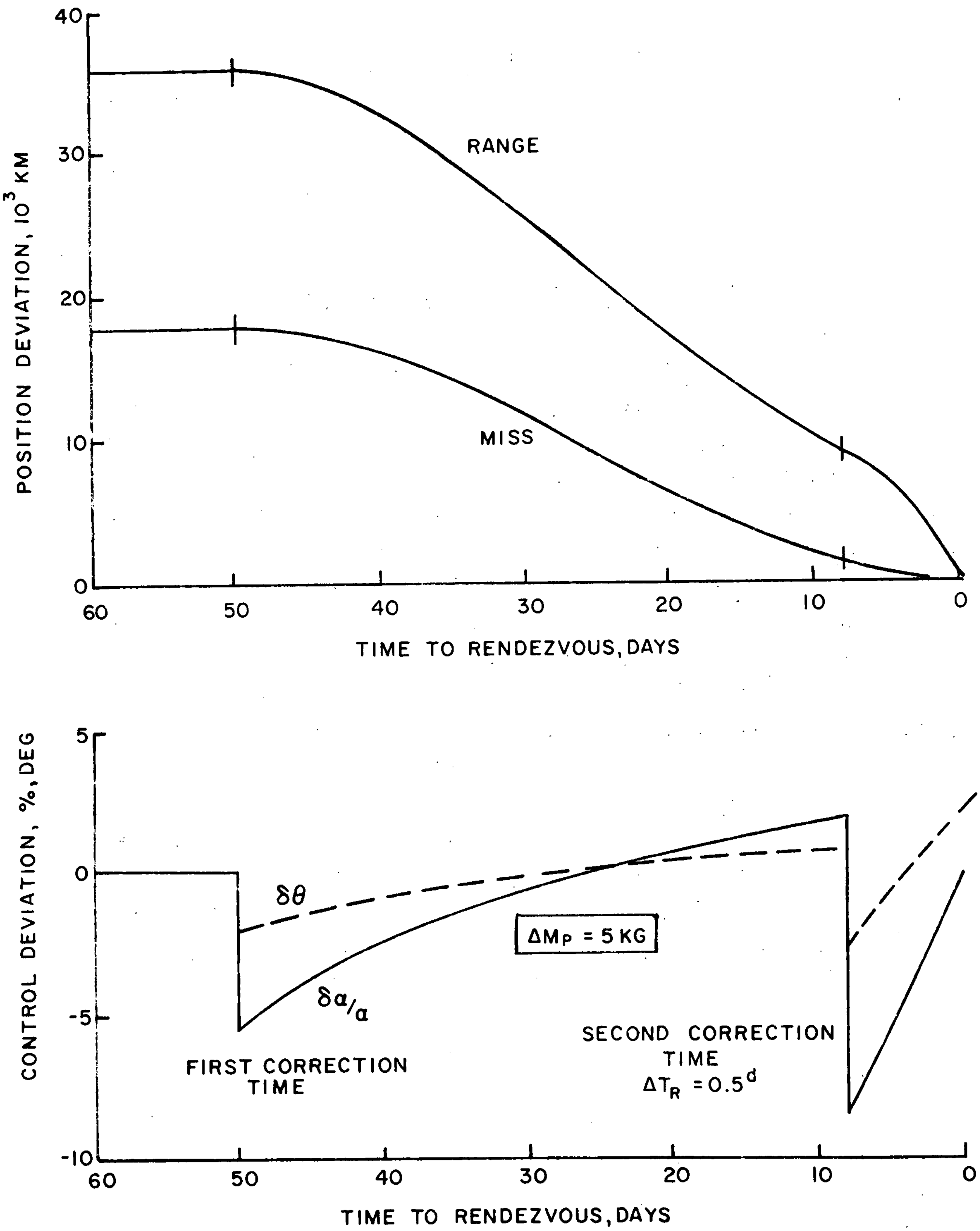


FIGURE 6-6. ILLUSTRATION OF TWO-CORRECTION GUIDANCE POLICY FOR SEP APPROACH TO P/ENCKE

STATIONKEEPING MANEUVERS NEAR P/ENCKE

The proposed stationkeeping/translation sequence begins 10 days after rendezvous (40 days before perihelion), and covers a total time interval of 60 days. The figure shows the translation paths, time points and the associated ΔV requirements. Plotted in a rotating coordinate frame centered at the comet, the translation paths are curvelinear under the influence of the differential solar gravity force. The spatial region covered is $\pm$ 20,000 km in the radial direction (solar reference axis), 8000 km in the forward circumferential direction, and 10,000 km in the rearward circumferential direction. Actually, the only true "stationkeeping" point occurs at $T_p = 10^d$ on the anti-solar axis. A ΔV expenditure of 39 m/sec is required to maintain the spacecraft at the 20,000 km distance for 10 days. This ΔV is distributed rather than being a single impulse, and is needed to compensate for the differential gravity force acting on the spacecraft. The total ΔV requirement for the maneuver sequence is 167 m/sec.

STATION POINT	TIME	ΔV (M/SEC)
1	$T_p - 40^d$	23
2	$T_p - 30^d$	45
3	$T_p - 10^d$	26
	REST	39
4	T_p	23
5	$T_p + 20^d$	11
		167 TOTAL

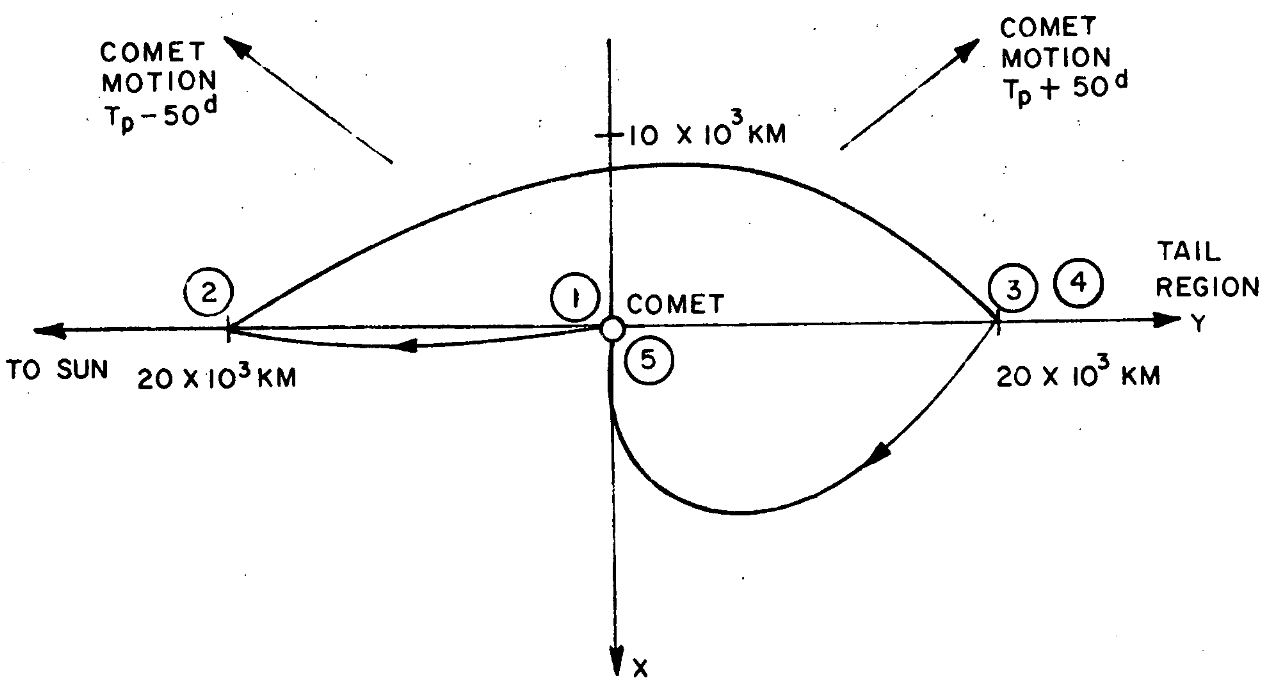


FIGURE 6-7.
STATIONKEEPING MANEUVERS NEAR P/ENCKE

FINAL TRANSLATION PATH IN VICINITY OF P/ENCKE

The facing figure shows a detail of the translation maneuver which returns the spacecraft to the immediate vicinity of the nucleus from a distance of 20,000 km on the anti-solar line (tail region). In particular, the broken line curve illustrates the effect of solar differential gravity if the spacecraft were left uncontrolled. After 10 days the spacecraft would move 23,000 km in the trailing direction. The 23 m/sec velocity impulse applied in the direction shown compensates for the gravity effect in addition to translating the spacecraft toward the nucleus. If differential gravity were absent, ΔV would only be 11.6 m/sec applied along the sun line.

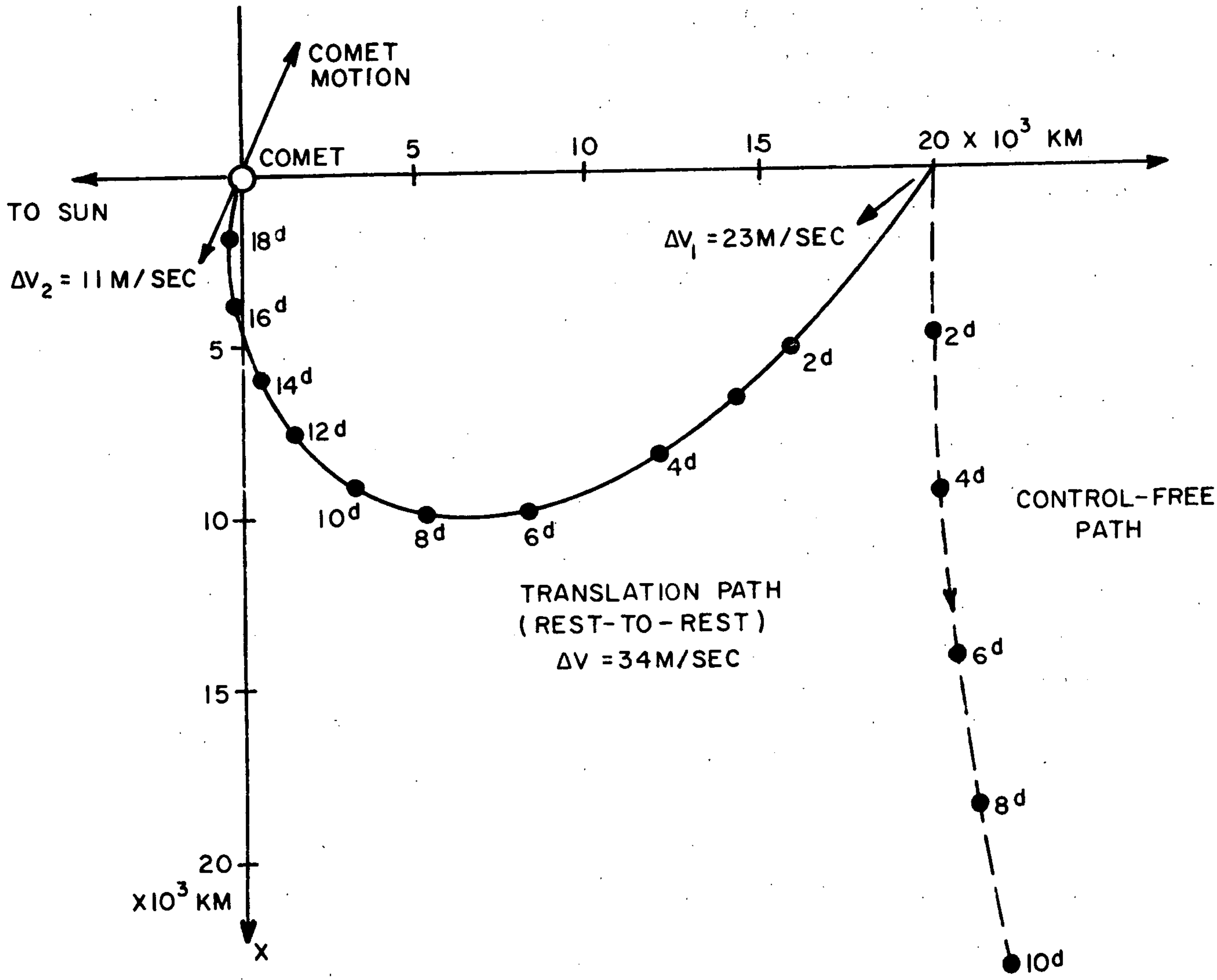


FIGURE 6-8. FINAL TRANSLATION PATH IN VICINITY OF P/ENCKE

STATIONKEEPING SUMMARY

The stationkeeping ΔV impulse requirement is listed for each of the four comet missions. Although the maneuver sequence and linear translation distance along the sun line are similar for each mission, there is a significant difference in ΔV requirement which should be explained. The two differentiating factors are the total time interval of stationkeeping and the comet's angular motion. If the time allowed for translating a given distance is longer then the ΔV required will obviously be lower. The angular motion variable relates to the ΔV required to maintain a station point in the tail region. A larger angular motion means that the differential gravity force is larger, and, hence, the ΔV is larger.

The maneuver/time sequence was determined on the basis of science considerations thought to be unique for each comet as discussed in Section 2 (e.g., the time of maximum tail activity). Obviously, there is some leeway in such a choice, and a more detailed mission analysis could easily result in modification of the proposed maneuver sequence.

Stationpoint	SEP P/Encke	SEP P/d'Arrest	SEP P/Kopff	SEP P/Halley
Leave nucleus vicinity	T_p-40^d	T_p-15^d	T_p-15^d	T_p-30^d
Arrive 20,000 km sunward	T_p-30^d	T_p	T_p	T_p-10^d
Arrive 20,000 km tailward	T_p-10^d	T_p+30^d	T_p+30^d	T_p+30^d
Leave tail region	T_p	T_p+40^d	T_p+40^d	T_p+50^d
Arrive nucleus vicinity	T_p+20^d	T_p+55^d	T_p+55^d	T_p+70^d

TABLE 6-2

STATIONKEEPING SUMMARY*

COMET	MAXIMUM ANGULAR MOTION	TIME INTERVAL	TOTAL ΔV
	DEG/DAY	DAYS	M/SEC
P/ENCKE	6.80	60	167
P/d'ARREST	0.85	70	94
P/KOPFF	0.62	70	93
P/HALLEY	3.08	100	69

* ± 20,000 km ABOUT SUNLINE

LOW THRUST STATIONKEEPING

Characteristics of performing the stationkeeping maneuvers with the solar electric propulsion system are shown for the P/Encke baseline mission. Average thrust acceleration available over the 60 day interval is 8×10^{-4} m/sec^2. The 167 m/sec ΔV requirement can be achieved with a propellant expenditure of only 6 kg and a total propulsion on-time of 2.4 days. The small 4% duty cycle should not seriously interfere with the science experiments. The proposed stationkeeping maneuvers require a relatively small separation between the thrust and solar directions. This implies a potential problem area if, for example, the thruster array were fixed at some large angle relative to the solar array axis. If this were a design constraint then the translation paths may have to be modified, e.g., by adding intermediate station points orthogonal to the sun line. Alternatively, the solar array could be off-pointed by as much as 60° which would increase the duty cycle to 8%. A rotatable solar array design would alleviate this potential problem area.

TABLE 6-3

LOW THRUST STATIONKEEPING

VELOCITY REQUIREMENT	167 M/SEC
THRUST ACCELERATION	8×10^{-4} M/SEC^2
PROPELLANT (I_{SP} = 3000 SEC)	6 kg
PROPULSION ON-TIME	2.4 DAYS
DUTY CYCLE (60 DAYS)	4 PERCENT

PROBLEM AREA:

MOST MANEUVERS REQUIRE THRUST DIRECTION WITHIN 25° OF SUNLINE OR ANTI-SUNLINE.

POSSIBLE SOLUTION:

(1) REDESIGN TRANSLATION PATHS

(2) ACCEPT COSINE-LOSS IN POWER AND INCREASED DUTY CYCLE.

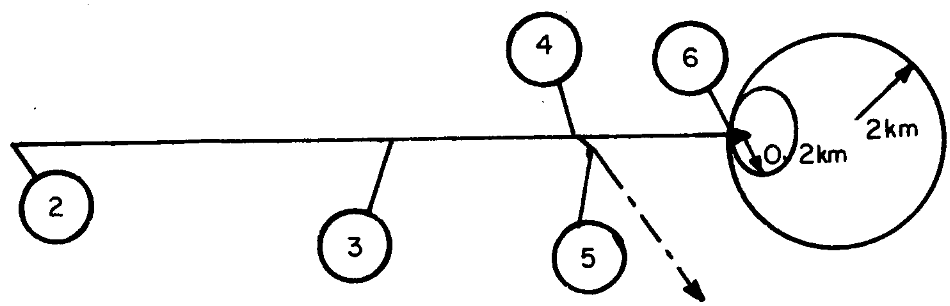
NUCLEUS PROBE DEPLOYMENT SEQUENCE

During the circumnavigation of the nucleus a landing site can be chosen for the probe. The deployment method used in this study is somewhat unique. No attitude control or propulsion system is required on the probe. Instead the probe and spacecraft are placed on a path leading to impact at the desired site. A correction in the direction of motion is made at the half way point. Then the probe is separated from the spacecraft and the spacecraft's path is changed to prevent it from impacting on the nucleus.

Velocities relative to the nucleus are small - about 1 m/sec. The targeting error will be about one-tenth the nucleus radius if the execution errors at points 2 and 3 are less than 5%.

FIGURE 6-9

NUCLEUS PROBE DEPLOYMENT SEQUENCE



NO.	EVENT	TIME *	RANGE
1.	SELECT LANDING SITE DURING CIRCUMNAVIGATION OF NUCLEUS	2-6[d]	—
2.	PUT SPACECRAFT ON DIRECT IMPACT PATH TO CHOSEN SITE	6.5	100 KM
3.	CORRECT PATH	7.0	50
4.	SEPARATE PROBE FROM SPACECRAFT	8.0	25
5.	CHANGE SPACECRAFT PATH	8.1	20
6.	PROBE IMPACT	8.5	0

* DAYS AFTER RENDEZVOUS

c

SECTION 7: ENCKE (1980) MISSION PROFILE

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SECTION 7 SUMMARY

Comet P/Encke has been selected in this study as being the favored target for a first-generation rendezvous mission. Good, consecutive opportunities are available at the 1980 and 1984 apparitions. Focusing attention on the earlier opportunity, this section describes characteristics of the mission profile from launch to the end of planned activity after rendezvous. The baseline mission utilizes a 15 kw SEP interplanetary spacecraft weighing 1200 kg and launched by the Titan 3D/Centaur. A two month launch window between February and April 1978 is available for an added propellant loading of only 15 kg. Nominally launched on March 2, the spacecraft arrives at P/Encke on Oct. 17, 1980 (50 days before perihelion) after a 960-day transfer. The propulsion power profile is matched by an array of 6 ion thrusters, each rated at 2.6 - 3 kw and having a 2:1 throttling capability. Maximum operating time for any single thruster is less than 6000 hours. At least one and as many as five thrusters are in standby condition during nominal propulsion periods. The wide variation of optimum thrust direction (relative to the sunline) can be achieved by a rotatable solar array design. P/Encke is approached from the sunward side. While this provides good illumination of the coma/nucleus, a potential viewing problem arises because the thrust beam must be pointed toward the comet during the approach. The approach navigation TV acquires the comet about 60 days before rendezvous. Picture transmission at intervals of one to two days would be quite adequate for guidance purposes. If desirable, the navigation data rate could be condensed by onboard pre-processing and transmittal of only significant information picture elements. Remote sensing science instruments begin operation about 30 days before rendezvous and collect data at a rate of about 6×10^7 bits per day. The data rate jumps to 3.5×10^8 bits per day during about 10 days of nucleus circumnavigation with the acquisition of 15 to 30 science

TV frames per day. Spacecraft coverage by DSN (Goldstone and Madrid) is at least 20 hours each day during all pre- and post-rendezvous operations. Finally, a preliminary analysis of Earth tracking by the spacecraft antenna indicates a cone angle variation between 10° and 130°, and also a significant clock angle variation. The antenna will therefore require two degrees of freedom, and thermal effects on the antenna surface structure must be considered.

Because the current NASA planetary program plan cannot accommodate a 1978 launch of a solar electric comet rendezvous mission, the subsequent study (TRW, 1972) will concentrate on the 1984 apparition of P/Encke.

OPERATIONS SCHEDULE FOR COMET P/ENCKE RENDEZVOUS MISSION

The timeline of operations for an Encke rendezvous mission is listed on the facing page. Total mission duration from the time of launch to the end of planned activity in the cometary environment is almost 3 years. Recall that there is an initial coast period of 266 days on the nominal trajectory. However, the operations schedule does identify an early period for thruster start-up and systems test. Correction of the launch vehicle guidance errors can also take place during this time. Spacecraft acquisition (on-board tracking) of the comet begins about 60 days before rendezvous. Although the nominal thruster start-up does not occur until 17 days later, some fraction of this coast period might be utilized for trajectory adjustment.

TABLE 7-1

OPERATIONS SCHEDULE FOR COMET P/ENCKE RENDEZVOUS MISSION

OPERATION	DATE		
LAUNCH (V_{HL} = 8.0 km/sec)	L + 0^d		3/ 2/78*
BEGIN COAST	+ 0		
THRUSTER TESTS/CORRECT LAUNCH ERRORS	+ 10		3/12/78
THRUSTERS ON /END COAST	+ 266		11/23/78
THRUSTERS OFF/BEGIN COAST	+ 784		4/24/80
EARTH BASED COMET RECOVERY	+ 860	R - 100^d	7/ 9/80
SPACECRAFT ACQUISITION OF COMET	+ 900	- 60	8/18/80
THRUST VECTOR PROGRAM UPDATE	+ 910	- 50	8/28/80
THRUSTERS ON/END COAST	+ 917		9/ 4/80
THRUST VECTOR PROGRAM UPDATE	+ 952	- 8	10/ 9/80
THRUSTERS OFF/RENDEZVOUS	+ 960^d	+ 0	10/17/80
BEGIN APPROACH TO NUCLEUS	P - 50^d	R + 0^d	10/17/80
ARRIVE (WITHIN 100 km) AT NUCLEUS	- 48	+ 2	10/19/80
CIRCUMNAVIGATE NUCLEUS	- 46	+ 4	10/23/80
DEPLOY NUCLEUS PROBE	- 42	+ 8	10/25/80
LEAVE NUCLEUS ALONG SUN LINE	- 40	+ 10	10/27/80
ARRIVE AT SUN LINE/20,000 km FROM NUCLEUS	- 30	+ 20	11/ 6/80
REVERSE MOTION/MOVE TOWARD TAIL	- 30	+ 20	11/ 6/80
ARRIVE AT TAIL/20,000 km FROM NUCLEUS/HOLD THIS POSITION	- 10	+ 40	11/26/80
LEAVE TAIL FOR NUCLEUS	+ 0	+ 50	12/ 6/80
ARRIVE NEAR NUCLEUS	+ 20	+ 70	12/26/80
CIRCUMNAVIGATE NUCLEUS	+ 22	+ 72	12/28/88
END PLANNED ACTIVITY/ BEGIN EXTENDED MISSION	+ 30	+ 80	1/ 5/81

L = LAUNCH; R = RENDEZVOUS; P = PERIHELION;
* MONTH/DAY/YEAR

ENCKE MISSION MASS ALLOCATION

A mass inventory of the baseline SEP mission to P/Encke is shown in the facing table. The net spacecraft mass includes the 130 kg of science instruments and nucleus probe. The total SEP system including propellant and tankage is 730 kg, or about 61% of the initial mass at Earth departure. Propellant loading accounts for an extended launch window, guidance and station-keeping maneuvers. Note that the Titan 3D/Centaur injected mass capability has a 300 kg growth margin.

TABLE 7-2

ENCKE MISSION MASS ALLOCATION

TITAN 3D/CENTAUR/SEP

P_0 = 15 KW, I_{SP} = 3000 SEC

SCIENCE INSTRUMENTS	70 kg
NUCLEUS PROBE	60
	130

NET SPACECRAFT AT RENDEZVOUS	470 kg
SOLAR ELECTRIC PROPULSION SYSTEM	450
MERCURY PROPELLANT AND TANKAGE	280
EARTH DEPARTURE MASS	1200
ADDED LV ADAPTER	60
INJECTED MASS	1260 kg
LV CAPABILITY AT V_{HL} = 8 KM/SEC INCLUDING DLA PENALTY	1560 kg

LAUNCH WINDOW CHARACTERISTICS FOR SEP MISSION TO P/ENCKE

The performance variation over the launch window is shown in the facing figure. Note that the assumed condition of fixed parameters implies no "physical" changes to the SEP/spacecraft stage once it is placed atop the launch vehicle, i.e., off-loading of mercury propellant is not required during an extended launch window. The upper graph shows the propellant requirements for the Earth-Encke transfer; in this case the additional propellant needed for guidance and stationkeeping maneuvers would be accounted for in the net spacecraft mass. A 66-day launch window provides a net mass capability of 500 kg. This is achieved at the expense of adding 15 kg to the nominal transfer propellant loading. Variation of flight time, propulsion time and DLA are tabulated below:

Launch	Flight Time	Propulsion Time	DLA
1/31/78	990 days	588 days	-32.2 deg
3/2/78	960 days	561 days	-44.8 deg
4/1/78	930 days	579 days	-37.8 deg

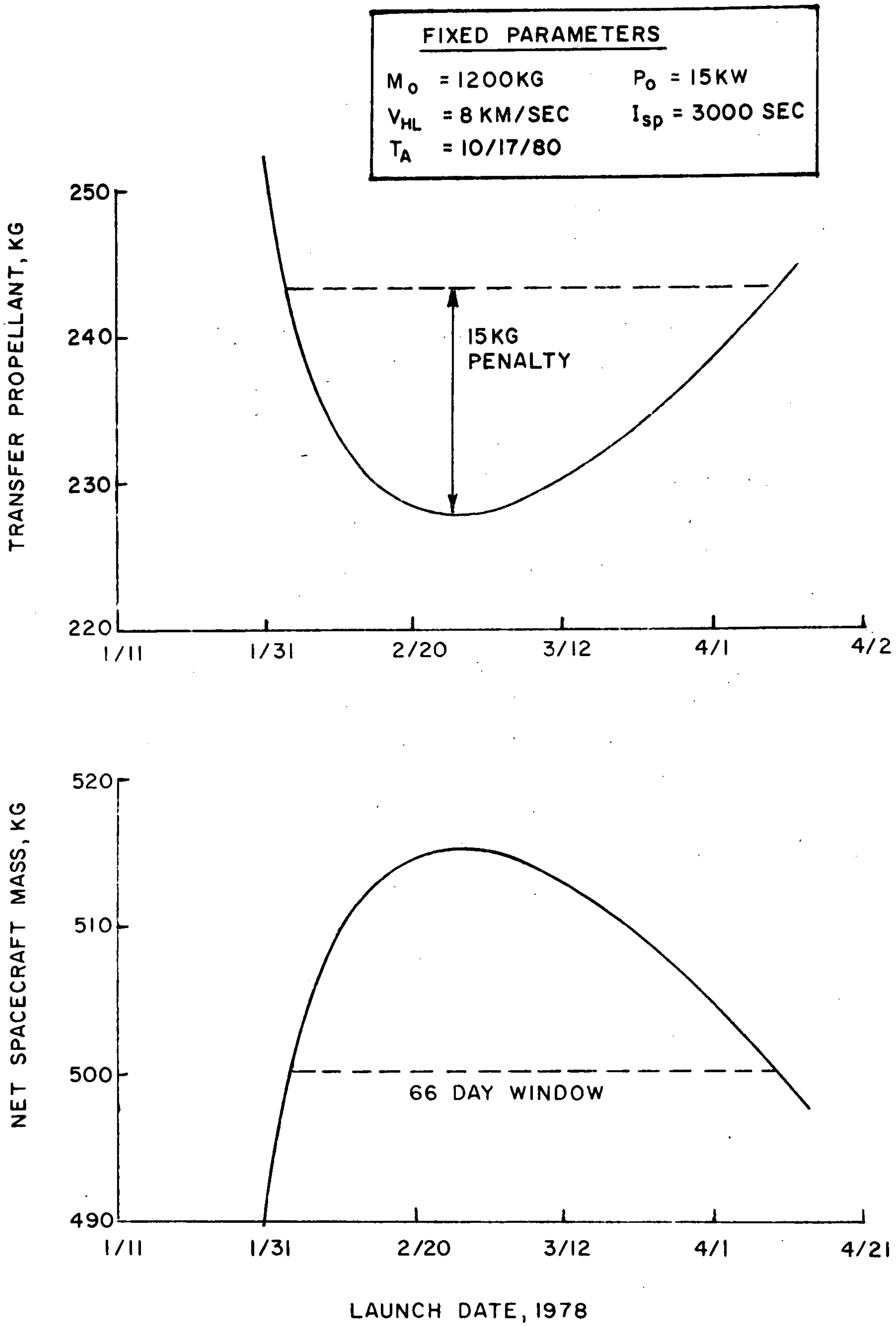


FIGURE 7-1. LAUNCH WINDOW CHARACTERISTICS FOR SEP MISSION TO P/ENCKE

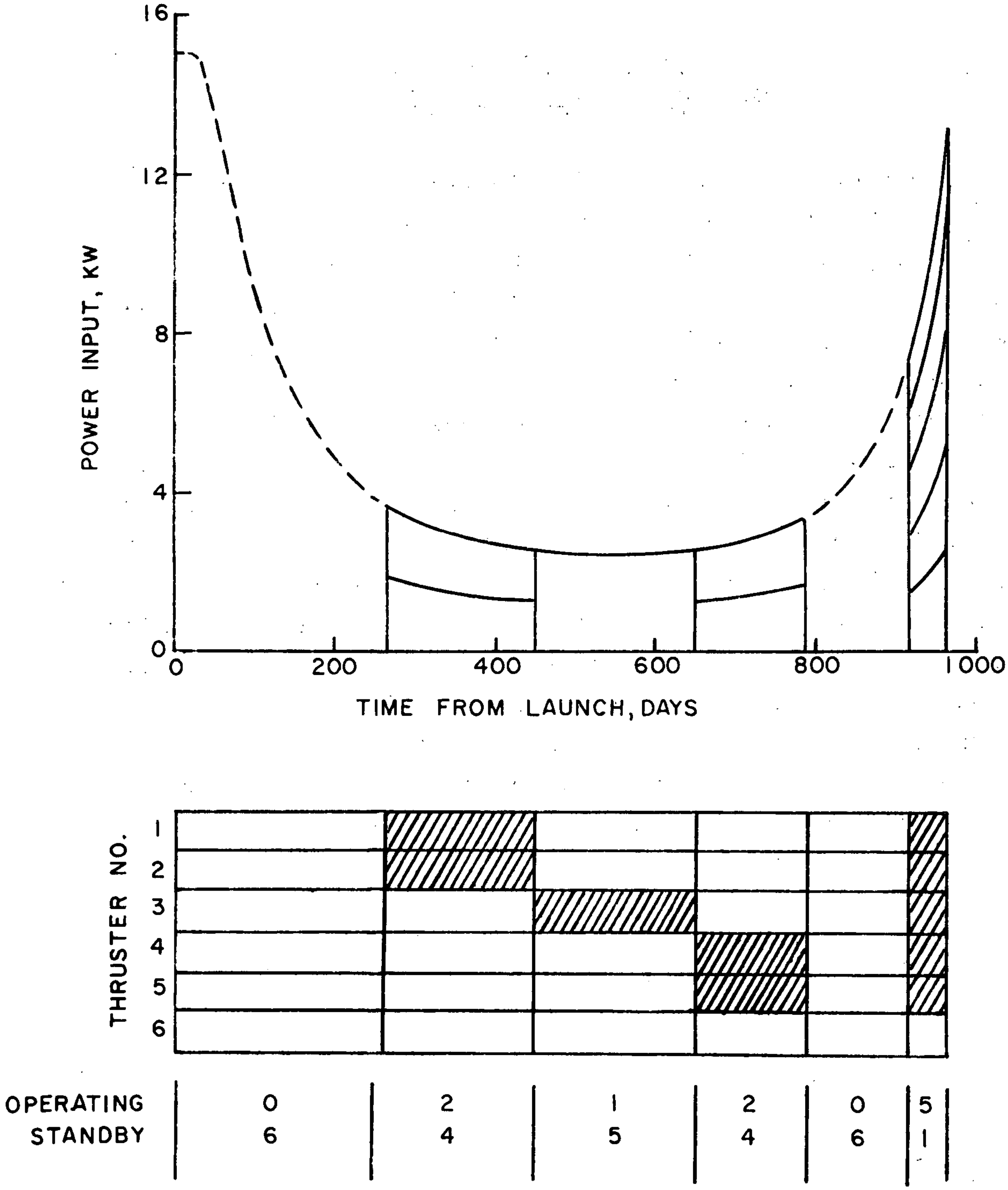
POWER PROFILE AND THRUSTER SWITCHING
ENCKE RENDEZVOUS MISSION

The variation of SEP power input is shown for the baseline mission to P/Encke. A broken line curve is used for the coast periods. The power profile is fairly flat over the mid-flight region but rises sharply during the 43-day terminal propulsion period where solar distance decreases rapidly. A representative thruster switching sequence is shown assuming that individual thrusters are rated at 2.6 kw with a two-to-one throttling capability. Maximum operating time for any single thruster is less than 6000 hours. If a 6-thruster array were employed there would be at least one and as many as five thrusters in standby during nominal propulsion periods. Note that the maximum number of thrusters is required during the last 40 days of the interplanetary transfer when, presumably, reliability is at a minimum. This is a characteristic disadvantage of SEP comet rendezvous - particularly, for the Encke mission.

FIGURE 7-2.

POWER PROFILE AND THRUSTER SWITCHING
ENCKE RENDEZVOUS MISSION

THRUSTER RATING	2.6-3.0 KW
THROTTLING RATIO	2:1
MAX. ON-TIME	6000 HRS.



THRUST VECTOR PROFILE FOR SEP MISSION TO P/ENCKE

Optimum thrust direction angles are shown as a function of time for the baseline mission to P/Encke. The cone angle is the displacement of the thrust vector from the solar direction and, hence, bears directly on the problem of mechanizing the steering program in the face of a solar array pointing constraint. Out-of-plane thrust direction can be obtained by rotating the spacecraft about the sunline. It is seen that the cone angle varies between 97° and 57° during the first propulsion period, but is less than 24° during the terminal propulsion period. Such a wide variation precludes a design approach whereby the thruster array is body-mounted at a fixed angle relative to the solar array. Rather, the solar array should have a single-axis rotation capability. This design approach would provide optimum thrust cone angles for both the heliocentric transfer and stationkeeping maneuvers near P/Encke, and is also necessary to provide thermal protection of the solar array at solar distances less than 0.65 AU.

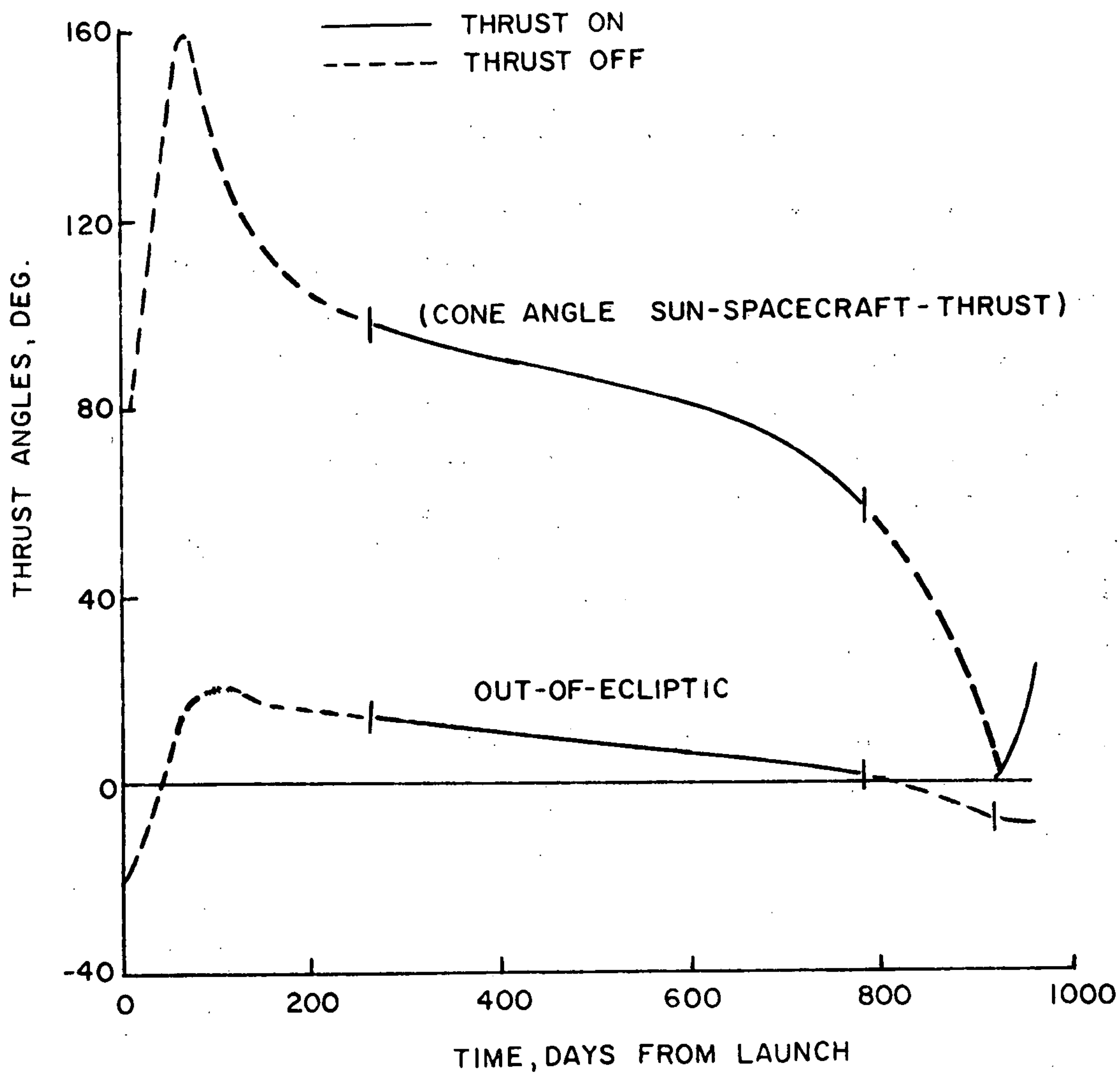


FIGURE 7-3. THRUST VECTOR PROFILE FOR SEP MISSION TO P/ENCKE

APPROACH PATH TO P/ENCKE

The approach to P/Encke during the 160 day interval prior to rendezvous is plotted in a comet-centered rotating coordinate frame. Direction to the Earth and the spacecraft's relative speed are indicated at several time points (160, 80 and 0 days). It is seen that the initial approach is from the solar direction and in the rearward hemisphere. The sunline is crossed at about 60 days to go and the final approach lies in the forward hemisphere. Although the comet nucleus will be illuminated by the sun throughout this approach, there is a potential viewing problem due to thrust vector pointing requirements. The thrust vector is opposite to the approach velocity direction which means that the thrust (ion beam) is pointed in the general direction of the comet line-of-sight.

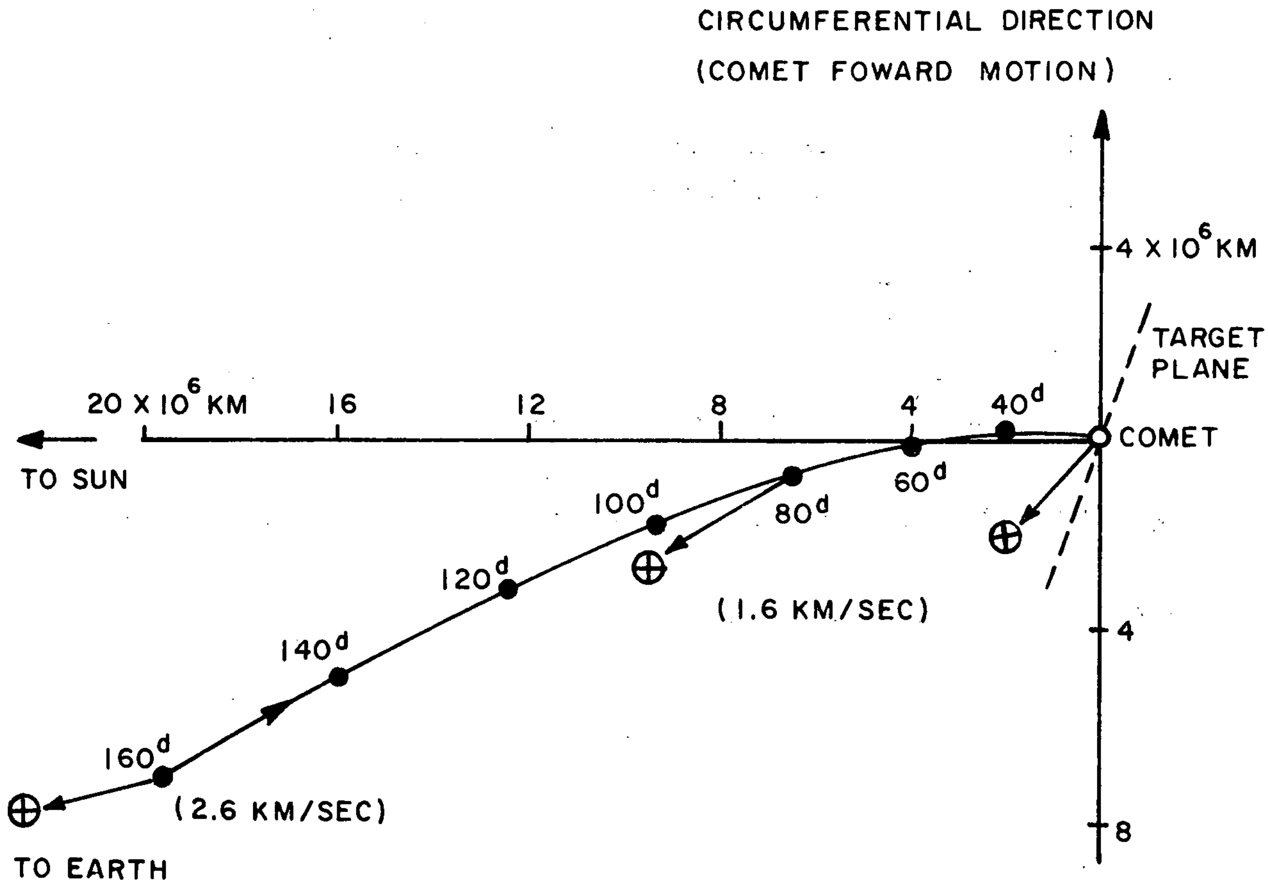


FIGURE 7-4. APPROACH PATH TO P/ENCKE

COMET MAGNITUDE AND RANGE ON APPROACH TO P/ENCKE

The brightness of P/Encke, in magnitude units, as seen from the spacecraft is plotted as a function of time to rendezvous. Assuming that the vidicon detectability threshold is 9th magnitude, on-board recovery occurs about 60 days before rendezvous at a range of 4×10^6 km. A threshold of 7th magnitude (typical of current systems) would delay recovery by about 20 days, but this would not seriously compromise the approach guidance function.

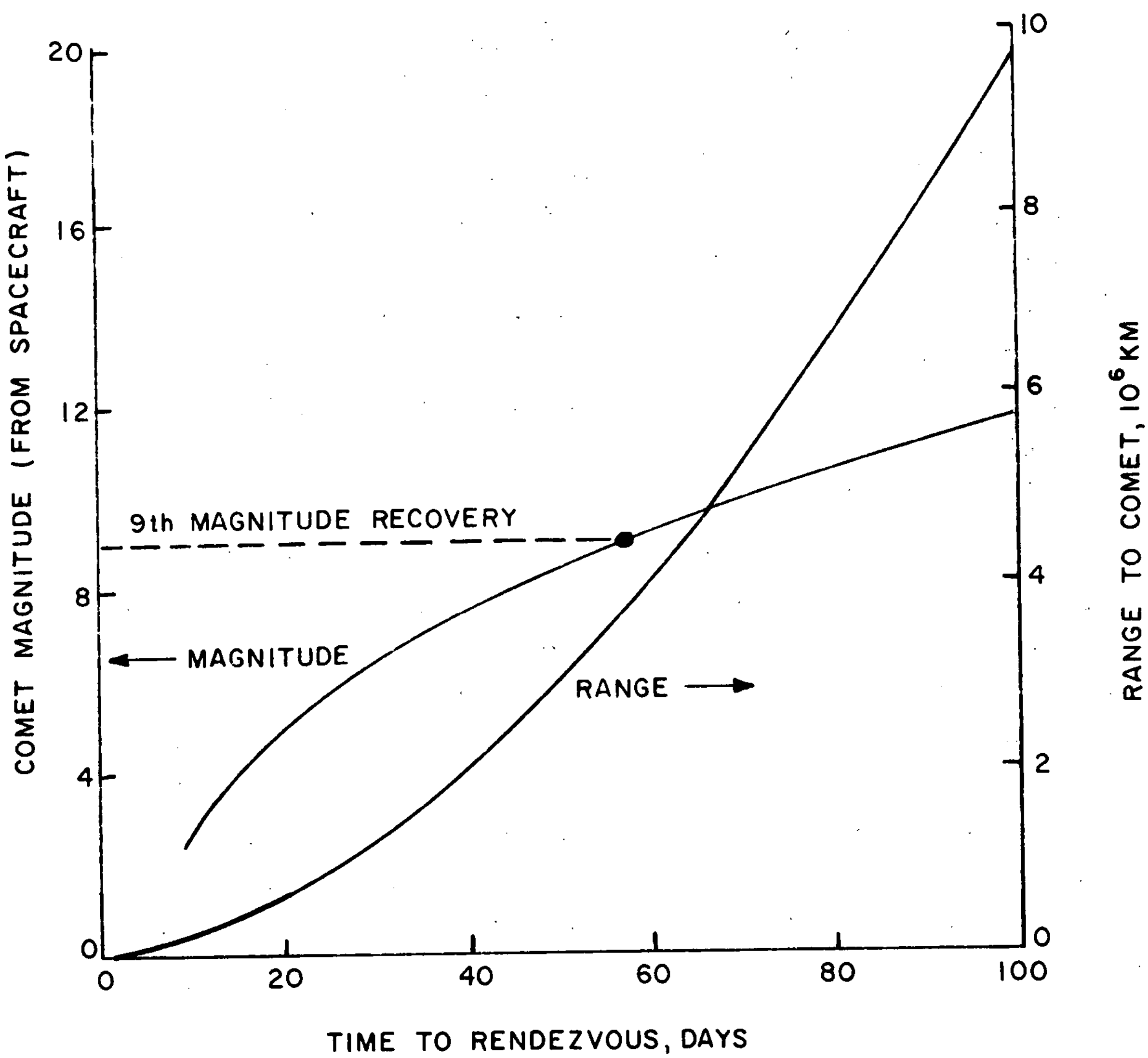


FIGURE 7-5. COMET MAGNITUDE AND RANGE ON APPROACH TO P/ENCKE.

SCIENCE INSTRUMENT OPERATION DURING P/ENCKE RENDEZVOUS MISSION

During the interplanetary transfer the fields and particles instruments will be in use, although probably at a lower data rate than they use during rendezvous. To (geometrically) calibrate the approach acquisition TV system it should be turned on before the predicted on-board recovery of the comet at 60 days before rendezvous. Daily updates of the location of the nucleus against the star background are required until rendezvous.

At about 30 days before the spacecraft arrives, when it is about one million kilometers from the nucleus, all instruments except the science TV should begin operation. The data collection rate will be about 6×10^7 bits per day. These instruments will be used as long as there is significant comet activity to observe or until at least 50 days after perihelion. Increases in the data rate can be expected during the two periods (ten days each) of nucleus circumnavigation. This is caused by the 30 frames per day taken with the science TV.

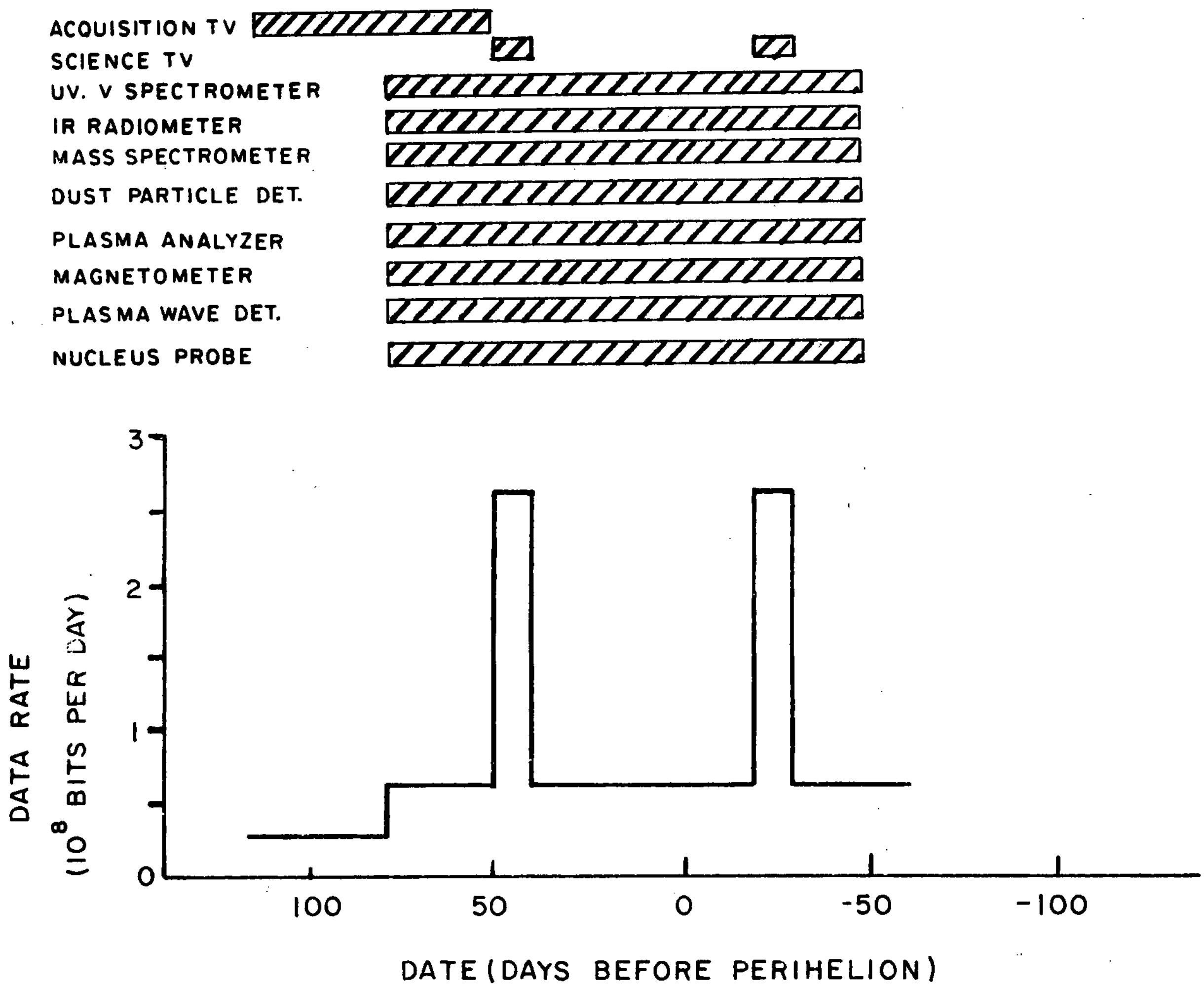


FIGURE 7-6. SCIENCE INSTRUMENT OPERATION DURING P/ENCKE RENDEZVOUS MISSION

DSN COVERAGE DURING P/ENCKE RENDEZVOUS MISSION

Using the predicted geocentric declination of P/Encke the time it spends above a 10° elevation is shown for DSN tracking stations at 35° N latitude (Goldstone and Madrid) and at 35° S (Astralia). Comet missions are unusual in that the spacecraft is sometimes at high declinations. For example P/Encke at $T_p - 50^d$ is at + 62°. This means that the comet is always in the sky as seen at Goldstone (latitude of 35° N) although only 20 hours are above 10° elevation for nominal DSN performance. With some help from Madrid good performance is assured at any time.

Also shown is the time per day during which at least one DSN station can acquire the spacecraft. Less than 24 hour availability occurs during periods centered on $T_p - 65^d$, $T_p - 35^d$ and $T_p + 25^d$. The first two occur because the comet sets at Goldstone before it rises in Madrid (and is not above the horizon in Australia). The last occurs because of gaps before and after Madrid acquires Encke.

For the other three comets the only DSN coverage problem occurs for P/Halley at $T_p + 60^d$ when the declination is - 46° and the comet cannot be acquired by Goldstone.

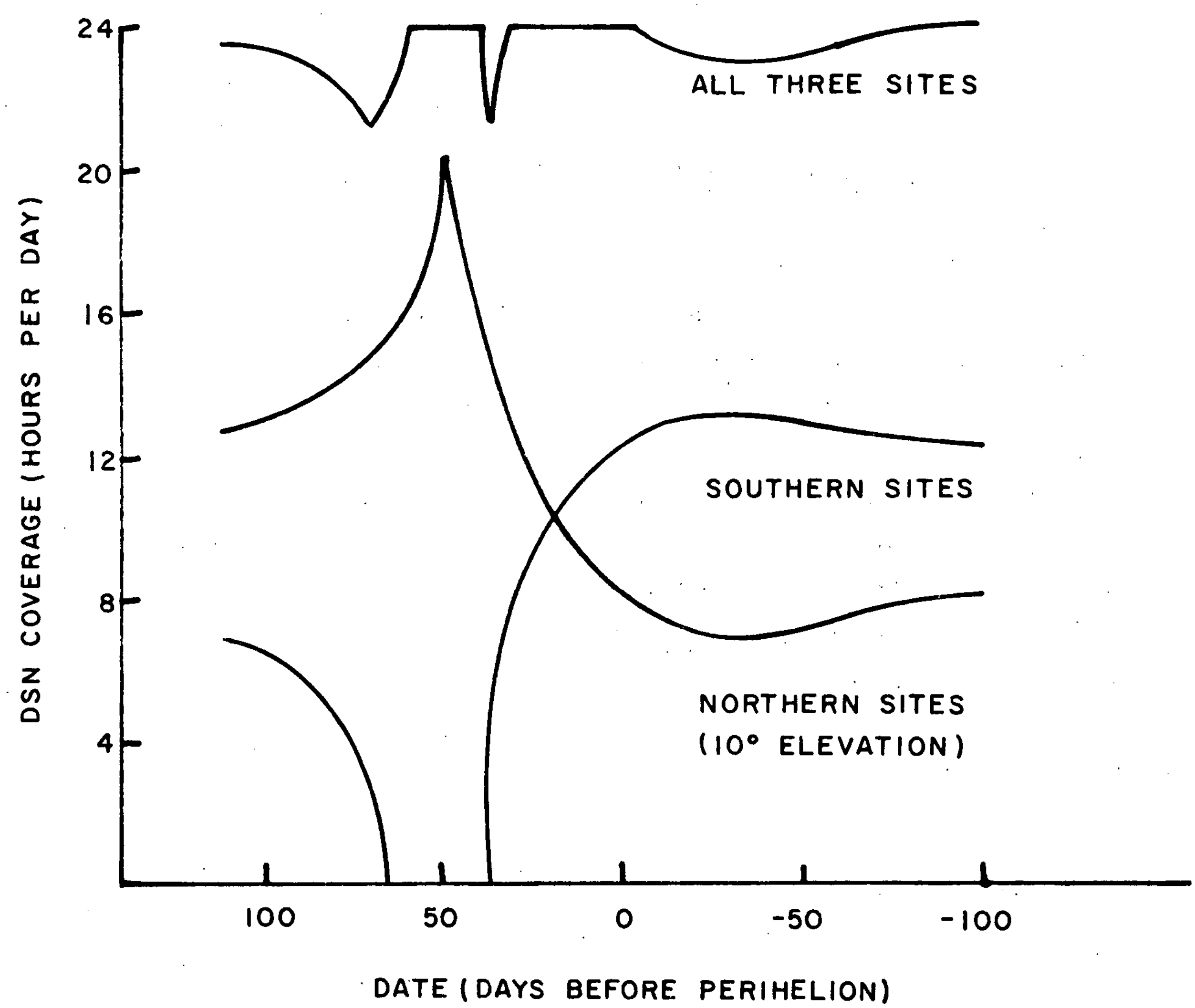


FIGURE 7-7. DSN COVERAGE DURING P/ENCKE RENDEZVOUS MISSION.

POSITION OF EARTH AS SEEN FROM P/ENCKE

While the spacecraft is near P/Encke the high gain antenna must be pointed toward the Earth for data transmission. The clock and cone angles of the Earth relative to the spacecraft solar reference frame are shown here. Because of large variations in both angles, the antenna must have two degress of freedom. Since the cone angle goes from 130 to 10 degrees, the sun will first illuminate the back and then the front of the parabolic dish. This plus the small perihelion distance (0.34 AU) of P/Encke will require that thermal effects on the antenna be considered.

Cone angle:	Angle between direction vectors to Sun and Earth measured at spacecraft.
Clock angle:	Angle between Spacecraft-Sun-Canopus plane and projection of Earth direction in a plane perpendicular to Sun direction, measured clockwise looking toward Sun.

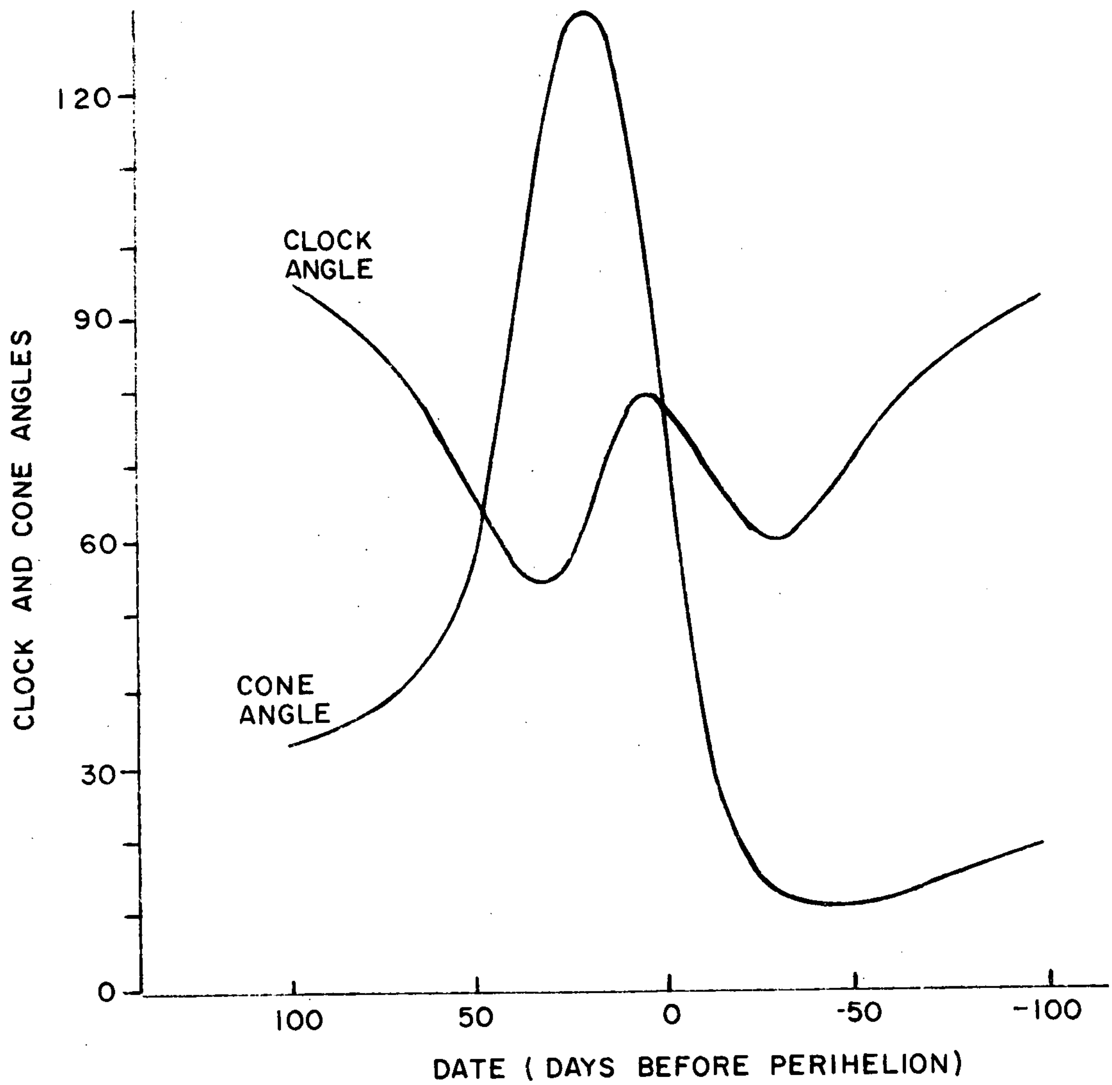


FIGURE 7-8. POSITION OF EARTH AS SEEN FROM P/ENCKE

8. CONCLUSIONS AND RECOMMENDATIONS

Two conditions should be used to select candidate comet apparitions. It is necessary to improve the comet orbit. Thus the comet should be recoverable by both Earth-based telescopes and on-board sensors about 50 days before rendezvous. Simultaneous Earth-based and spacecraft observation of the comet will be important for the improvement that will result in the understanding of previous (and future) comet observations. Therefore the candidate comet should be easily observed from the Earth during at least one month near its perihelion. In addition, the arrival date and mission duration should be selected to cover both increasing and decreasing comet activity. Four comets (and the year in which they return to perihelion) which meet these criteria are P/Encke (1980 and 1984), P/d'Arrest (1982) P/Kopff (1983) and P/Halley (1986). The most active periodic comet is P/Halley. P/Encke is interesting because a vast amount of data has been collected on it. The other two candidates are typical short-period comets.

The scientific interest in comets is related to their origin. Is a comet a sample of the early solar system or of interstellar material? Thus exploration objectives are concerned primarily with the composition of cometary material and the morphology of the comet nucleus. A comprehensive study of the spatial structure and temporal behavior of periodic comets can also be made during a rendezvous mission. Spatially there are three important regions: the small icy nucleus, the coma containing gas molecules and solid particles, and the tails, one ionized, the other dusty.

The spacecraft should be equipped with both remote sensing and in-situ instruments. These two types are complimentary, the latter determines the conditions near the spacecraft while the former provides data on the conditions farther away. An example of a complimentary pair is the UV, V spectrometer and the mass spectrometer which both measure molecular and ion abundances. Similarly the photometer/radiometer and the solid particle detector both measure the extent of dust in the coma. Two vidicon camera systems are needed, one to acquire the comet before rendezvous and the other to obtain images of the nucleus.

Following rendezvous a stationkeeping program, such as the one proposed, should be carried out. Radial traverses to 20,000 km from the nucleus can be used to study the spatial structure in the coma and the origin of the ion and dust tails. To collect remote sensing data on the nucleus, circumnavigations of this small body at a distance of 100 km are useful. In-situ exploration of the nucleus is best accomplished using a deployed probe. This concept balances overall science data return and spacecraft complexity since it allows the in-situ data to be collected without additional hazard to the spacecraft and with little interruption in the program to explore the coma.

The selected science instruments (including 10% growth) have a total weight of about 70 kg and a data load of 2.6×10^8 bits per day. Most of the instruments are currently available. The deployed probe is estimated at 60 kg. The net spacecraft mass, including 200 m/sec of ΔV capability for midcourse or stationkeeping maneuvers, is approximately 500 kg.

Rendezvous missions to the short-period comets, Encke, d'Arrest and Kopff, can be accomplished ballistically using a Titan 3D(7)/Centaur launch vehicle and a high energy upper stage ($I_{sp} \approx 400$ sec). Solar electric propulsion (SEP) is preferred because it performs these missions in a shorter time (less than 2.6 years) and has a larger payload margin. Rendezvous with all three comets can be accomplished using the programmed Titan 3D/Centaur and a 15 kw SEP power plant with an I_{sp} of 300 sec. Total thrust time is less than 15,000 hours, but less than 6,000 hours for any one thruster. Optimum thrust vector pointing was assumed and can be implemented with rotating solar arrays. For some missions, a fixed thrust direction should be possible with some increase in propulsion time. There are no advantages to jettisoning the SEP system at rendezvous. Thus an integrated design (SEP and spacecraft) is preferred since it will be smaller and since the SEP can be used for the stationkeeping program.

Practical accomplishment of the very difficult rendezvous with P/Halley depends upon the development of nuclear electric propulsion by 1983. A 100 kw NEP system launched to Earth escape by a Titan 3D(7)/Centaur (or better yet by a Shuttle/Centaur) can easily deliver more than the desired payload. With a 2.6 year flight time and only 15,000 hours of propulsion time, the payload is 500 kg. SEP and ballistic trajectories to P/Halley using Jupiter gravity assist have much longer flight times (more than seven years) and marginal payloads.

The effects of velocity errors at Earth departure and during interplanetary transfer can be measured by the DSN and the necessary corrections are easily made at a cost of less than 100 m/sec for ballistic missions and less than 10 kg additional propellant for SEP cases. Coast periods in the SEP missions are essential for acquisition of accurate position and velocity data by the DSN. At rendezvous the major error source is the uncertainty in the comet ephemeris. This error will be reduced to many thousands of kilometers following Earth-based recovery and ultimately to less than 100 km by the on-board approach acquisition system. A non-zero value for the miss distance is required to reduce the range uncertainty.

For two reasons P/Encke is favored for a first generation rendezvous. Scientifically P/Encke is more interesting than other short-period comets. The planning can be more flexible because there are favorable apparitions in 1980 and 1984. Rendezvous with P/Encke is, however, somewhat more demanding than the P/d'Arrest or P/Kopff missions.

Further study of rendezvous missions to the periodic comets at the Phase A level, with emphasis on a solar electric mission to P/Encke at either the 1980 or 1984 apparition, is warranted.* Areas requiring more detailed analysis include: 1) a model for the comet environment, 2) a design for a nucleus probe, 3) the performance penalty for constrained (non-optimum) thrust vector steering and 4) an engineering design for the spacecraft which considers thermal control and the pointing requirements for the science instruments, the antenna and the thrust vector. A flythrough mission would simplify the solution of some of these engineering problems. Technology advances are needed to develop the remote control techniques and/or on-board decision making system to be used during the stationkeeping program, the approach guidance TV (or alternate system) and new science instruments for composition determinations of solid particles and energetic ions.

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* For budgetary reasons, NASA has decided that the subsequent comet rendezvous study (TRW, 1972) will concentrate on 1981 and 1982 launches to P/Encke.

REFERENCES

Biermann, L. (1971), "Gaseous Atmospheres of Comets," Nature 230, 156-159.

Biermann, L., Brosowski, B., and Schmidt, H. U. (1967), "The Interaction of the Solar Wind with a Comet," Solar Physics 1, 254-284.

Bobrovnikoff, N. T. (1927) "On the Spectrum of Halley's Comet," Astrophys. J. 66, 145-169.

Bobrovnikoff, N. T. (1931) "Halley's Comet in its Apparition of 1909-1911," Publ. Lick. Obs. 17, 305-482.

Brady, J. L. and Carpenter, E. (1971) "The Orbit of Halley's Comet and the Apparition of 1986," Astron. J. 76, 728-739.

Delsemme, A. H. and Miller, D. C. (1970), "Physio-Chemical Phenomena in Comets - II, Planet. Sp. Sci. 18, 717-730.

Dossin, F. (1965), "Observations Spectroscopiques de Quelques Comètes en 1964 et 1965," Inst. d'Astrophys. Univ. Liège, coll 4° No. 162.

Edsinger, L. (1971), "Parametric Sizing of Unmanned Spacecraft," to be published.

Finson, M. L. and Probstein, R. F. (1968), "A Theory of Dust Comets. II. Results for Arend-Roland," Astrophys. J. 154, 353-380.

Friedlander, A. L. (1970), Solar Electric Propulsion - A Survey, Technology Status and Mission Applications, IIT Research Institute/Astro Sciences Report M-21, March 1970.

Friedlander, A. L., Niehoff, J. C., and Waters, J. I., (1970), Trajectory and Propulsion Characteristics of Comet Rendezvous Opportunities, IIT Research Institute/Astro Sciences Report T-25, August 1970.

Gardner, J. A. (1971), 1976 d'Arrest Comet Mission Study, JPL Document No. 760-66, 10 May 1971.

Hahn, D. W., et.al. (1969), "Chebychev Trajectory Optimization Program (CHEBYTOP)," Report No. D2-121308-1, Boeing Company, July 1969.

JPL (1968), Capsule System Advanced Development Program Report, JPL Document 760-29, 15 July 1968.

JPL (1971), Solar Electric Multimission Spacecraft (SEMMS), JPL Report No. 617-2, 30 July 1971.

Kennet, H. and Spear, E. E. (1969), "Spacecraft Sizing Technique for Planetary Missions," AIAA Paper No. 69-125, AIAA 7th Aerospace Sciences Meeting, New York, N. Y., Jan. 20-22.

Klopp, D. A. and Wells, W. C. (1971), Mercury Orbiter Mission Study, IIT Research Institute/Astro Sciences Report No. M-26.

Kresák, L. (1965), "On the Secular Variations in the Absolute Brightness of Periodic Comets," Bull. Astr. Inst. Csl. 16, 348-355.

Marsden, B. G. (1970), "Comets and Nongravitational Forces III," Astron. J. 75, 75-84.

Mianes, P., Grudzinska, S. and Stawikowski, A. (1960) "Observations Physiques de la Comète Périodique Giacobini-Zinner," Ann. Astrophys. 23, 788-796.

Narin, F. and Pierce, P. M. (1964), Perturbations, Sighting and Trajectory Analysis for Periodic Comets: 1965-1975, N66-13398, IIT Research Institute/Astro Sciences Report No. T-7.

Narin, F. and Rejzer, B. (1965), Sighting and Trajectory Analysis for Periodic Comets: 1976-1986, N65-28347, IIT Research Institute/Astro Sciences Report No. T-11.

Nier, A. O. and Hayden, J. L. (1971), "A Miniature Mattauch-Herzog Mass Spectrometer for the Investigation of Planetary Atmospheres," Int. J. Mass Spectrom. Ion Phys. 6, 339-346.

O'Dell, C. R. and Roberts, D. L., eds. (1971), Proceedings of the Cometary Science Working Group, Yerkes Observatory, Williams Bay, Wisconsin, June 1971.

Oort, J. H. (1950), "The Structure of the Cloud of Comets Surrounding the Solar System, and a Hypothesis Concerning its Origin," Bull. of the Astron. Inst. of the Netherlands 11, 91-110.

Oort, J. H. (1951), "The Origin and Development of Comets," The Observatory 71, 129-144.

Oort, J. H. (1963), "Empirical Data on the Origin of Comets," in The Moon, Meteorites and Comets, B. M. Middlehurst and G. P. Kuiper eds. (Univ. of Chicago Press: Chicago).

Rahe, J., Donn, B. and Wurm, K. (1969), Atlas of Cometary Forms (NASA (SP-198): Washington, D. C.).

Rourke, K. H. and Jordan, J. F. (1971), "Guidance and Navigation for Solar Electric Interplanetary Missions," J. Spacecraft and Rockets 8, 920-926.

Schaupp, R. W. and Sawyer, C. D. (1971), "Applications of Nuclear Reactor Power Systems to Electric Propulsion Missions," paper presented at the 1971 Thermionic Conversion Specialist Conference.

Sekanina, Z. (1970), IAUC Circular No. 2276 on Brightness Assymetry of Encke.

Swings, P., Fehrenbach, C. and Woszczyk, A. (1957), "Le Spectre de le Comète 1957c (Encke)," Comptes Rendus 245, 2152-2155.

TRW (1972), Study of a Comet Rendezvous Mission, Final Report on JPL contract No. 953247, to be published.

TRW (1971), Study of a Common Solar-Electric-Propulsion Upper Stage for High-Energy Unmanned Missions, Vol. II, Final Report on Contract NASZ-6040, 14 July 1971.

Vsekhsvyatskii, (1964), Physical Characteristics of Comets, (Israel Program for Scientific Translations: Jurusalem).

Waters, J. I. (1971), "Application of an Impulsive Trajectory Optimization Method to the Comet Rendezvous Problem," AIAA Paper No. 71-93, AIAA 9th Aerospace Sciences Meeting, Jan. 25-27, 1971.

Whipple, F. L. (1950) "Comet Model I. The Acceleration of Comet Encke," Astrophys. J. 111, 375-394.

Whipple, F. L. (1951), "Comet Model II. Physical Relations for Comets and Meteors," Astrophys. J. 113, 464-475.

Whipple, F. L. (1955), "Comet Model III. The Zodiacal Light," Astrophys. J. 121, 750-770.

Whipple, F. L. (1963), "On the Structure of the Cometary Nucleus," in The Moon, Meteorites and Comets, B. M. Middlehurst and G. P. Kuiper eds. (Univ. of Chicago Press: Chicago).

White, R. E. (1970), IAUC Circular No. 2267.